

PATENT APPLICATION

**MICROFABRICATED ELASTOMERIC VALVE  
AND PUMP SYSTEMS**

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## MICROFABRICATED ELASTOMERIC VALVE AND PUMP SYSTEMS

### CROSS-REFERENCE TO RELATED APPLICATIONS

5           This nonprovisional patent application is a continuation-in-part of parent nonprovisional patent application 09/605,520, filed June 27, 2000. The parent application claims the benefit of the following previously filed provisional patent applications: U.S. provisional patent application no. 60/141,503 filed June 28, 1999, U.S. provisional patent application no. 60/147,199 filed August 3, 1999, and U.S. provisional patent application  
10 no. 60/186,856 filed March 3, 2000. The text of these prior provisional patent applications is hereby incorporated by reference.

### 15           STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

Work described herein has been supported, in part, by National Institute of Health grant HG-01642-02. The United States Government may therefore have certain rights in the invention.

### TECHNICAL FIELD

20           The present invention relates to microfabricated structures and methods for producing microfabricated structures, and to microfabricated systems for regulating fluid-flow.

### BACKGROUND OF THE INVENTION

25           Various approaches to designing micro-fluidic pumps and valves have been attempted. Unfortunately, each of these approaches suffers from its own limitations.

The two most common methods of producing microelectromechanical (MEMS) structures such as pumps and valves are silicon-based bulk micro-machining (which is a subtractive fabrication method whereby single crystal silicon is

type materials such as polysilicon, silicon nitride, silicon dioxide, and various polymers sequentially added and patterned to make three-dimensional structures).

A limitation of the first approach of silicon-based micro-machining is that the stiffness of the semiconductor materials used necessitates high actuation forces, which in turn result in large and complex designs. In fact, both bulk and surface micro-machining methods are limited by the stiffness of the materials used. In addition, 5 adhesion between various layers of the fabricated device is also a problem. For example, in bulk micro-machining, wafer bonding techniques must be employed to create multilayer structures. On the other hand, when surface micro-machining, thermal stresses between the various layers of the device limits the total device thickness, often to approximately 20 microns. Using either of the above methods, clean room fabrication 10 and careful quality control are required.

### SUMMARY OF THE INVENTION

The present invention sets forth systems for fabricating and operating microfabricated structures such as on/off valves, switching valves, and pumps e.g. made 15 out of various layers of elastomer bonded together. The present structures and methods are ideally suited for controlling and channeling fluid movement, but are not so limited.

In a preferred aspect, the present invention uses a multilayer soft lithography process to build integrated (i.e.: monolithic) microfabricated elastomeric structures.

20 Advantages of fabricating the present structures by binding together layers of soft elastomeric materials include the fact that the resulting devices are reduced by more than two orders of magnitude in size as compared to silicon-based devices. Further advantages of rapid prototyping, ease of fabrication, and biocompatibility are also achieved.

25 In preferred aspects of the invention, separate elastomeric layers are fabricated on top of micromachined molds such that recesses are formed in each of the various elastomeric layers. By bonding these various elastomeric layers together, the recesses extending along the various elastomeric layers form flow channels and control will be explained.

between the surface of the planar substrate and the recesses which extend along the bottom surface of the elastomeric structure.

In one preferred aspect, the present monolithic elastomeric structures are constructed by bonding together two separate layers of elastomer with each layer first  
5 being separately cast from a micromachined mold. Preferably, the elastomer used is a two-component addition cure material in which the bottom elastomeric layer has an excess of one component, while the top elastomeric layer has an excess of another component. In an exemplary embodiment, the elastomer used is silicone rubber. Two layers of elastomer are cured separately. Each layer is separately cured before the top  
10 layer is positioned on the bottom layer. The two layers are then bonded together. Each layer preferably has an excess of one of the two components, such that reactive molecules remain at the interface between the layers. The top layer is assembled on top of the bottom layer and heated. The two layers bond irreversibly such that the strength of the interface approaches or equals the strength of the bulk elastomer. This creates a  
15 monolithic three-dimensional patterned structure composed entirely of two layers of bonded together elastomer. Additional layers may be added by simply repeating the process, wherein new layers, each having a layer of opposite "polarity" are cured, and thereby bonded together.

In a second preferred aspect, a first photoresist layer is deposited on top of  
20 a first elastomeric layer. The first photoresist layer is then patterned to leave a line or pattern of lines of photoresist on the top surface of the first elastomeric layer. Another layer of elastomer is then added and cured, encapsulating the line or pattern of lines of photoresist. A second photoresist layer is added and patterned, and another layer of elastomer added and cured, leaving line and patterns of lines of photoresist encapsulated  
25 in a monolithic elastomer structure. This process may be repeated to add more encapsulated patterns and elastomer layers. Thereafter, the photoresist is removed leaving flow channel(s) and control line(s) in the spaces which had been occupied by the photoresist. This process may be repeated to create elastomer structures having a

a photoresist method is that a high-resolution transparency mask is used as a master mask. This allows a single researcher to design, print, pattern the mold, and create a new



and 10 ms. The cycling speeds depend upon the composition and structure of a valve used for a particular application and the method of actuation, and thus cycling speeds outside of the listed ranges would fall within the scope of the present invention.

Further advantages of the present pumps and valves are that their small size makes them fast and their softness contributes to making them durable. Moreover, as they close linearly with differential applied pressure, this linear relationship allows fluid metering and valve closing in spite of high back pressures.

In various aspects of the invention, a plurality of flow channels pass through the elastomeric structure with a second flow channel extending across and above a first flow channel. In this aspect of the invention, a thin membrane of elastomer separates the first and second flow channels. As will be explained, downward movement of this membrane (due to the second flow channel being pressurized or the membrane being otherwise actuated) will cut off flow passing through the lower flow channel.

In optional preferred aspects of the present systems, a plurality of individually addressable valves are formed connected together in an elastomeric structure and are then activated in sequence such that peristaltic pumping is achieved. More complex systems including networked or multiplexed control systems, selectably addressable valves disposed in a grid of valves, networked or multiplexed reaction chamber systems and biopolymer synthesis systems are also described.

One embodiment of a microfabricated elastomeric structure in accordance with the present invention comprises an elastomeric block formed with first and second microfabricated recesses therein, a portion of the elastomeric block deflectable when the portion is actuated.

One embodiment of a method of microfabricating an elastomeric structure comprises the steps of microfabricating a first elastomeric layer, microfabricating a second elastomeric layer, positioning the second elastomeric layer on top of the first elastomeric layer, and bonding a bottom surface of the second elastomeric layer onto a top surface of the first elastomeric layer.

protrusion which forms at least one first channel in the bottom surface of the first

protrusion which forms at least one second channel in the bottom surface of the second elastomeric layer. The bottom surface of the second elastomeric layer is bonded onto a top surface of the first elastomeric layer such that the at least one second channel is enclosed between the first and second elastomeric layers.

5           A second alternative embodiment of a method of microfabricating an elastomeric structure in accordance with the present invention comprises the steps of forming a first elastomeric layer on top of a substrate, curing the first elastomeric layer, and depositing a first sacrificial layer on the top surface of the first elastomeric layer. A portion of the first sacrificial layer is removed such that a first pattern of sacrificial  
10 material remains on the top surface of the first elastomeric layer. A second elastomeric layer is formed over the first elastomeric layer thereby encapsulating the first pattern of sacrificial material between the first and second elastomeric layers. The second elastomeric layer is cured and then sacrificial material is removed thereby forming at least one first recess between the first and second layers of elastomer.

15           An embodiment of a method of actuating an elastomeric structure in accordance with the present invention comprises providing an elastomeric block formed with first and second microfabricated recesses therein, the first and second microfabricated recesses being separated by a portion of the structure which is deflectable into either of the first or second recesses when the other of the first and second recesses.  
20 One of the recesses is pressurized such that the portion of the elastomeric structure separating the second recess from the first recess is deflected into the other of the two recesses.

          In other optional preferred aspects, magnetic or conductive materials can be added to make layers of the elastomer magnetic or electrically conducting, thus  
25 enabling the creation of all elastomer electromagnetic devices.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a method of microfabricating an elastomeric structure in accordance with the present invention. The method includes the steps of forming a first elastomeric layer on top of a substrate, curing the first elastomeric layer, and depositing a first sacrificial layer on the top surface of the first elastomeric layer. A portion of the first sacrificial layer is removed such that a first pattern of sacrificial material remains on the top surface of the first elastomeric layer. A second elastomeric layer is formed over the first elastomeric layer thereby encapsulating the first pattern of sacrificial material between the first and second elastomeric layers. The second elastomeric layer is cured and then sacrificial material is removed thereby forming at least one first recess between the first and second layers of elastomer.

FIG. 2 is a schematic diagram of a method of actuating an elastomeric structure in accordance with the present invention. The method includes the steps of providing an elastomeric block formed with first and second microfabricated recesses therein, the first and second microfabricated recesses being separated by a portion of the structure which is deflectable into either of the first or second recesses when the other of the first and second recesses.

Fig. 3 is an illustration of the elastomeric layer of Fig. 2 removed from the micromachined mold and positioned over the top of the elastomeric layer of Fig. 1

Fig. 4 is an illustration corresponding to Fig. 3, but showing the second elastomeric layer positioned on top of the first elastomeric layer.

5 Fig. 5 is an illustration corresponding to Fig. 4, but showing the first and second elastomeric layers bonded together.

Fig. 6 is an illustration corresponding to Fig. 5, but showing the first micromachine mold removed and a planar substrate positioned in its place.

10 Fig. 7A is an illustration corresponding to Fig. 6, but showing the elastomeric structure sealed onto the planar substrate.

Figs. 7B is a front sectional view corresponding to Fig. 7A, showing an open flow channel.

Figs. 7C-7G are illustrations showing steps of a method for forming an elastomeric structure having a membrane formed from a separate elastomeric layer.

15 **Part II - Fig. 7H show the closing of a first flow channel by pressurizing a second flow channel, as follows:**

Fig. 7H corresponds to Fig. 7A, but shows a first flow channel closed by pressurization in second flow channel.

20 **Part III - Figs. 8 to 18 illustrate successive steps of a second method of fabricating the present invention, as follows:**

Fig. 8 is an illustration of a first elastomeric layer deposited on a planar substrate.

25 Fig. 9 is an illustration showing a first photoresist layer deposited on top of the first elastomeric layer of Fig. 8.

Fig. 10 is an illustration showing the system of Fig. 9, but with a portion of the first photoresist layer removed, leaving only a first line of photoresist.

the photoresist between the first and second elastomeric layers.

Fig. 12 corresponds to Fig. 11, but shows the integrated monolithic



Fig. 13 is an illustration showing a second photoresist layer deposited on top of the integral elastomeric structure of Fig. 12.

Fig. 14 is an illustration showing the system of Fig. 13, but with a portion of the second photoresist layer removed, leaving only a second line of photoresist.

5 Fig. 15 is an illustration showing a third elastomer layer applied on top of the second elastomeric layer and over the second line of photoresist of Fig. 14, thereby encapsulating the second line of photoresist between the elastomeric structure of Fig. 12 and the third elastomeric layer.

10 Fig. 16 corresponds to Fig. 15, but shows the third elastomeric layer cured so as to be bonded to the monolithic structure composed of the previously bonded first and second elastomer layers.

Fig. 17 corresponds to Fig. 16, but shows the first and second lines of photoresist removed so as to provide two perpendicular overlapping, but not intersecting, flow channels passing through the integrated elastomeric structure.

15 Fig. 18 is an illustration showing the system of Fig. 17, but with the planar substrate thereunder removed.

**Part IV - Figs. 19 and 20 show further details of different flow channel cross-sections, as follows:**

20 Fig. 19 shows a rectangular cross-section of a first flow channel.

Fig. 20 shows the flow channel cross section having a curved upper surface.

**Part V - Figs. 21 to 24 show experimental results achieved by preferred  
25 embodiments of the present microfabricated valve:**

Fig. 21 illustrates valve opening vs. applied pressure for various flow channels.

Fig. 22 illustrates time response of a  $100\mu\text{m} \times 100\mu\text{m} \times 10\mu\text{m}$  RTV

**Part VI - Figs. 25 A to 25 show various microfabricated structures, networked together according to aspects of the present invention:**

Fig. 23B is a sectional elevation view along line 23B-23B in Fig. 23A

Fig. 24 is a top schematic view of a peristaltic pumping system.

Fig. 24B is a sectional elevation view along line 24B-24B in Fig. 24A

Fig. 25 is a graph showing experimentally achieved pumping rates vs.  
5 frequency for an embodiment of the peristaltic pumping system of Fig. 24.

Fig. 26A is a top schematic view of one control line actuating multiple  
flow lines simultaneously.

Fig. 26B is a sectional elevation view along line 26B-26B in Fig. 26A

Fig. 27 is a schematic illustration of a multiplexed system adapted to  
10 permit flow through various channels.

Fig. 28A is a plan view of a flow layer of an addressable reaction chamber  
structure.

Fig. 28B is a bottom plan view of a control channel layer of an addressable  
reaction chamber structure.

15 Fig. 28C is an exploded perspective view of the addressable reaction  
chamber structure formed by bonding the control channel layer of Fig 28B to the top of  
the flow layer of Fig 28A.

Fig. 28D is a sectional elevation view corresponding to Fig. 28C, taken  
along line 28D-28D in Fig. 28C.

20 Fig. 29 is a schematic of a system adapted to selectively direct fluid flow  
into any of an array of reaction wells.

Fig. 30 is a schematic of a system adapted for selectable lateral flow  
between parallel flow channels.

Fig. 31A is a bottom plan view of first layer (i.e.: the flow channel layer)  
25 of elastomer of a switchable flow array.

Fig. 31B is a bottom plan view of a control channel layer of a switchable  
flow array.

Fig. 31C shows the alignment of the first layer of elastomer of Fig. 31A  
with one set of control channels in the second layer of elastomer of Fig. 31B

Fig. 32 is a schematic of an integrated system for biopolymer synthesis.

Fig. 33 is a schematic of a further integrated system for biopolymer

Fig. 34 is an optical micrograph of a section of a test structure having seven layers of elastomer bonded together.

Figs. 35A-35D show the steps of one embodiment of a method for fabricating an elastomer layer having a vertical via formed therein.

5 Fig. 36 shows one embodiment of a sorting apparatus in accordance with the present invention.

Fig. 37 shows an embodiment of an apparatus for flowing process gases over a semiconductor wafer in accordance with the present invention.

10 Fig. 38 shows an exploded view of one embodiment of a micro-mirror array structure in accordance with the present invention.

Fig. 39 shows a perspective view of a first embodiment of a refractive device in accordance with the present invention.

Fig. 40 shows a perspective view of a second embodiment of a refractive device in accordance with the present invention.

15 Fig. 41 shows a perspective view of a third embodiment of a refractive device in accordance with the present invention.

Figs. 42A-42J show views of one embodiment of a normally-closed valve structure in accordance with the present invention.

20 Figs. 43 shows a plan view of one embodiment of a device for performing separations in accordance with the present invention.

Figs. 44A-44D show plan views illustrating operation of one embodiment of a cell pen structure in accordance with the present invention.

Figs. 45A-45B show plan and cross-sectional views illustrating operation of one embodiment of a cell cage structure in accordance with the present invention.

25 Figs. 46A-46B show cross-sectional views illustrating operation of one embodiment of a cell grinder structure in accordance with the present invention.

Fig. 47 shows a plan view of one embodiment of a pressure oscillator structure in accordance with the present invention.

FIG. 48A and 48B illustrate an alternative embodiment of one

elastomer with GE SF96-50 silicone fluid.

FIG. 49 is a perspective view of one embodiment of a pressure oscillator

Figure 51 shows a cross-sectional view of a structure in which non-channel bearing faces are placed into contact and then sandwiched between two substrates.

5        Figures 52A-52C show cross-sectional views of the steps for constructing a bridging structure. Figure 52D shows a plan view of the bridging structure.

Figure 53 shows a cross-sectional view of one embodiment of a composite structure in accordance with the present invention.

10        Figure 54 shows a cross-sectional view of one embodiment of a composite structure in accordance with the present invention.

## **DETAILED DESCRIPTION OF THE PRESENT INVENTION**

The present invention comprises a variety of microfabricated elastomeric structures which may be used as pumps or valves. Methods of fabricating the preferred elastomeric structures are also set forth.

15

### Methods of Fabricating the Present Invention:

Two exemplary methods of fabricating the present invention are provided herein. It is to be understood that the present invention is not limited to fabrication by one or the other of these methods. Rather, other suitable methods of fabricating the present microstructures, including modifying the present methods, are also contemplated.

20

Figs. 1 to 7B illustrate sequential steps of a first preferred method of fabricating the present microstructure, (which may be used as a pump or valve). Figs. 8 to 18 illustrate sequential steps of a second preferred method of fabricating the present microstructure, (which also may be used as a pump or valve).

25

As will be explained, the preferred method of Figs. 1 to 7B involves using pre-cured elastomer layers which are assembled and bonded. Conversely, the preferred method of Figs. 8 to 18 involves curing each layer of elastomer "in place". In the following description "channel" refers to a recess in the elastomeric structure which can contain a flow of fluid.

### The First Exemplary Method

Referring to Fig. 1, a first micro-machined mold 10 is provided. Micro-

methods, including but not limited to photolithography, ion-milling, and electron beam lithography.

As can be seen, micro-machined mold 10 has a raised line or protrusion 11 extending therealong. A first elastomeric layer 20 is cast on top of mold 10 such that a first recess 21 will be formed in the bottom surface of elastomeric layer 20, (recess 21 corresponding in dimension to protrusion 11), as shown.

As can be seen in Fig. 2, a second micro-machined mold 12 having a raised protrusion 13 extending therealong is also provided. A second elastomeric layer 22 is cast on top of mold 12, as shown, such that a recess 23 will be formed in its bottom surface corresponding to the dimensions of protrusion 13.

As can be seen in the sequential steps illustrated in Figs. 3 and 4, second elastomeric layer 22 is then removed from mold 12 and placed on top of first elastomeric layer 20. As can be seen, recess 23 extending along the bottom surface of second elastomeric layer 22 will form a flow channel 32.

Referring to Fig. 5, the separate first and second elastomeric layers 20 and 22 (Fig. 4) are then bonded together to form an integrated (i.e.: monolithic) elastomeric structure 24.

As can be seen in the sequential step of Figs. 6 and 7A, elastomeric structure 24 is then removed from mold 10 and positioned on top of a planar substrate 14. As can be seen in Fig. 7A and 7B, when elastomeric structure 24 has been sealed at its bottom surface to planar substrate 14, recess 21 will form a flow channel 30.

The present elastomeric structures form a reversible hermetic seal with nearly any smooth planar substrate. An advantage to forming a seal this way is that the elastomeric structures may be peeled up, washed, and re-used. In preferred aspects, planar substrate 14 is glass. A further advantage of using glass is that glass is transparent, allowing optical interrogation of elastomer channels and reservoirs. Alternatively, the elastomeric structure may be bonded onto a flat elastomer layer by the same method as described above, forming a permanent and high-strength bond. This may prove

comprising an elongated channel 32 formed in the bottom surface of elastomeric structure 24, the top of flow channel 30 from the bottom of flow channel 32.

the top of flow channel 30 from the bottom of flow channel 32.

further advantage of using glass is that optical sensing may be employed. Alternatively, planar substrate 14 may be an elastomer itself, which may prove advantageous when higher back pressures are used.

5 The method of fabrication just described may be varied to form a structure having a membrane composed of an elastomeric material different than that forming the walls of the channels of the device. This variant fabrication method is illustrated in Figs. 7C-7G.

Referring to Fig. 7C, a first micro-machined mold 10 is provided. Micro-machined mold 10 has a raised line or protrusion 11 extending therealong. In Fig. 7D,  
10 first elastomeric layer 20 is cast on top of first micro-machined mold 10 such that the top of the first elastomeric layer 20 is flush with the top of raised line or protrusion 11. This may be accomplished by carefully controlling the volume of elastomeric material spun onto mold 10 relative to the known height of raised line 11. Alternatively, the desired shape could be formed by injection molding.

15 In Fig. 7E, second micro-machined mold 12 having a raised protrusion 13 extending therealong is also provided. Second elastomeric layer 22 is cast on top of second mold 12 as shown, such that recess 23 is formed in its bottom surface corresponding to the dimensions of protrusion 13.

In Fig. 7F, second elastomeric layer 22 is removed from mold 12 and  
20 placed on top of third elastomeric layer 222. Second elastomeric layer 22 is bonded to third elastomeric layer 20 to form integral elastomeric block 224 using techniques described in detail below. At this point in the process, recess 23 formerly occupied by raised line 13 will form flow channel 23.

In Fig. 7G, elastomeric block 224 is placed on top of first micro-machined  
25 mold 10 and first elastomeric layer 20. Elastomeric block and first elastomeric layer 20 are then bonded together to form an integrated (i.e.: monolithic) elastomeric structure 24 having a membrane composed of a separate elastomeric layer 222.

When elastomeric structure 24 has been sealed at its bottom surface to a

The variant fabrication method illustrated above in conjunction with Figs. 7C-7G offers the advantage of permitting the membrane portion to be composed of a

different elastomeric material than that forming the walls of the channels of the device. This may be advantageous when higher back pressures are used, as the membrane portion may be composed of a more robust elastomeric material than the channel walls.

operation of the device. Moreover, this method allows the separate elastomer layer to readily be subjected to conditioning prior to incorporation into the elastomer structure. As discussed in detail below, examples of potentially desirable condition include the introduction of magnetic or electrically conducting species to permit actuation of the membrane, and/or the introduction of dopant into the membrane in order to alter its elasticity.

While the above method is illustrated in connection with forming various shaped elastomeric layers formed by replication molding on top of a micromachined mold, the present invention is not limited to this technique. Other techniques could be employed to form the individual layers of shaped elastomeric material that are to be bonded together. For example, a shaped layer of elastomeric material could be formed by laser cutting or injection molding, or by methods utilizing chemical etching and/or sacrificial materials as discussed below in conjunction with the second exemplary method.

#### **The Second Exemplary Method:**

A second exemplary method of fabricating an elastomeric structure which may be used as a pump or valve is set forth in the sequential steps shown in Figs. 8-18.

In this aspect of the invention, flow and control channels are defined by first patterning photoresist on the surface of an elastomeric layer (or other substrate, which may include glass) leaving a raised line photoresist where a channel is desired. Next, a second layer of elastomer is added thereover and a second photoresist is patterned on the second layer of elastomer leaving a raised line photoresist where a channel is desired. A third layer of elastomer is deposited thereover. Finally, the photoresist is removed by dissolving it out of the elastomer with an appropriate solvent, with the voids formed by removal of the photoresist becoming the flow channels passing through the substrate.

Referring first to Fig. 8, a planar substrate 40 is provided. A first

first line of photoresist 44B remains as shown. Referring to Fig. 11, a second elastomeric

elastomeric layer 42 and second elastomeric layer 46. Referring to Fig. 12, elastomeric layers 46 is then cured on layer 42 to bond the layers together to form a monolithic elastomeric substrate 45.

Referring to Fig. 13, a second photoresist layer 48A is then deposited over elastomeric structure 45. Referring to Fig. 14, a portion of second photoresist layer 48A is removed, leaving only a second photoresist line 48B on top of elastomeric structure 45 as shown. Referring to Fig. 15, a third elastomeric layer 50 is then deposited over the top of elastomeric structure 45 (comprised of second elastomeric layer 42 and first line of photoresist 44B) and second photoresist line 48B as shown, thereby encasing the second line of photoresist 48B between elastomeric structure 45 and third elastomeric layer 50.

Referring to Fig. 16, third elastomeric layer 50 and elastomeric structure 45 (comprising first elastomeric layer 42 and second elastomeric layer 46 bonded together) is then bonded together forming a monolithic elastomeric structure 47 having photoresist lines 44B and 48B passing therethrough as shown. Referring to Fig. 17, photoresist lines 44B, 48B are then removed (for example, by a solvent ) such that a first flow channel 60 and a second flow channel 62 are provided in their place, passing through elastomeric structure 47 as shown. Lastly, referring to Fig. 18, planar substrate 40 can be removed from the bottom of the integrated monolithic structure.

The method described in Figs. 8-18 fabricates a patterned elastomer structure utilizing development of photoresist encapsulated within elastomer material. However, the methods in accordance with the present invention are not limited to utilizing photoresist. Other materials such as metals could also serve as sacrificial materials to be removed selective to the surrounding elastomer material, and the method would remain within the scope of the present invention. For example, as described in detail below in connection with Figs. 35A-35D, gold metal may be etched selective to RTV 615 elastomer utilizing the appropriate chemical mixture.

#### Preferred Layer and Channel Dimensions:

Various dimensions of the various layers and channels of the monolithic structures are provided on a micron level, with at least one dimension being microscopic (i.e. below 1000  $\mu\text{m}$ ).



as photolithography and spincoating that are designed for to produce feature dimensions on the microscopic level, with at least some of the dimension of the microfabricated structure requiring a microscope to reasonably resolve image the structure.

In preferred aspects, flow channels 30, 32, 60 and 62 preferably have  
5 width-to-depth ratios of about 10:1. A non-exclusive list of other ranges of width-to-depth ratios in accordance with embodiments of the present invention is 0.1:1 to 100:1, more preferably 1:1 to 50:1, more preferably 2:1 to 20:1, and most preferably 3:1 to 15:1. In an exemplary aspect, flow channels 30, 32, 60 and 62 have widths of about 1 to 1000 microns. A non-exclusive list of other ranges of widths of flow channels in accordance  
10 with embodiments of the present invention is 0.01 to 1000 microns, more preferably 0.05 to 1000 microns, more preferably 0.2 to 500 microns, more preferably 1 to 250 microns, and most preferably 10 to 200 microns. Exemplary channel widths include 0.1  $\mu\text{m}$ , 1  $\mu\text{m}$ , 2  $\mu\text{m}$ , 5  $\mu\text{m}$ , 10  $\mu\text{m}$ , 20  $\mu\text{m}$ , 30  $\mu\text{m}$ , 40  $\mu\text{m}$ , 50  $\mu\text{m}$ , 60  $\mu\text{m}$ , 70  $\mu\text{m}$ , 80  $\mu\text{m}$ , 90  $\mu\text{m}$ , 100  $\mu\text{m}$ , 110  $\mu\text{m}$ , 120  $\mu\text{m}$ , 130  $\mu\text{m}$ , 140  $\mu\text{m}$ , 150  $\mu\text{m}$ , 160  $\mu\text{m}$ , 170  $\mu\text{m}$ , 180  $\mu\text{m}$ , 190  $\mu\text{m}$ , 200  
15  $\mu\text{m}$ , 210  $\mu\text{m}$ , 220  $\mu\text{m}$ , 230  $\mu\text{m}$ , 240  $\mu\text{m}$ , and 250  $\mu\text{m}$ .

Flow channels 30, 32, 60, and 62 have depths of about 1 to 100 microns. A non-exclusive list of other ranges of depths of flow channels in accordance with embodiments of the present invention is 0.01 to 1000 microns, more preferably 0.05 to 500 microns, more preferably 0.2 to 250 microns, and more preferably 1 to 100 microns,  
20 more preferably 2 to 20 microns, and most preferably 5 to 10 microns. Exemplary channel depths include including 0.01  $\mu\text{m}$ , 0.02  $\mu\text{m}$ , 0.05  $\mu\text{m}$ , 0.1  $\mu\text{m}$ , 0.2  $\mu\text{m}$ , 0.5  $\mu\text{m}$ , 1  $\mu\text{m}$ , 2  $\mu\text{m}$ , 3  $\mu\text{m}$ , 4  $\mu\text{m}$ , 5  $\mu\text{m}$ , 7.5  $\mu\text{m}$ , 10  $\mu\text{m}$ , 12.5  $\mu\text{m}$ , 15  $\mu\text{m}$ , 17.5  $\mu\text{m}$ , 20  $\mu\text{m}$ , 22.5  $\mu\text{m}$ , 25  $\mu\text{m}$ , 30  $\mu\text{m}$ , 40  $\mu\text{m}$ , 50  $\mu\text{m}$ , 75  $\mu\text{m}$ , 100  $\mu\text{m}$ , 150  $\mu\text{m}$ , 200  $\mu\text{m}$ , and 250  $\mu\text{m}$ .

The flow channels are not limited to these specific dimension ranges and  
25 examples given above, and may vary in width in order to affect the magnitude of force required to deflect the membrane as discussed at length below in conjunction with Fig. 27. For example, extremely narrow flow channels having a width on the order of 0.01  $\mu\text{m}$  may be useful in optical and other applications, as discussed in detail below.

applications of utilizing such wider flow channels include fluid reservoir and mixing channel structures.

Elastomeric layer 22 may be cast thick for mechanical stability. In an exemplary embodiment, layer 22 is 50 microns to several centimeters thick, and more preferably approximately 4 mm thick. A non-exclusive list of ranges of thickness of the elastomer layer in accordance with other embodiments of the present invention is  
5 between about 0.1 micron to 10 cm, 1 micron to 5 cm, 10 microns to 2 cm, 100 microns to 10 mm.

Accordingly, membrane 25 of Fig. 7B separating flow channels 30 and 32 has a typical thickness of between about 0.01 and 1000 microns, more preferably 0.05 to 500 microns, more preferably 0.2 to 250, more preferably 1 to 100 microns, more  
10 preferably 2 to 50 microns, and most preferably 5 to 40 microns. As such, the thickness of elastomeric layer 22 is about 100 times the thickness of elastomeric layer 20.  
Exemplary membrane thicknesses include 0.01  $\mu\text{m}$ , 0.02  $\mu\text{m}$ , 0.03  $\mu\text{m}$ , 0.05  $\mu\text{m}$ , 0.1  $\mu\text{m}$ , 0.2  $\mu\text{m}$ , 0.3  $\mu\text{m}$ , 0.5  $\mu\text{m}$ , 1  $\mu\text{m}$ , 2  $\mu\text{m}$ , 3  $\mu\text{m}$ , 5  $\mu\text{m}$ , 7.5  $\mu\text{m}$ , 10  $\mu\text{m}$ , 12.5  $\mu\text{m}$ , 15  $\mu\text{m}$ , 17.5  $\mu\text{m}$ , 20  $\mu\text{m}$ , 22.5  $\mu\text{m}$ , 25  $\mu\text{m}$ , 30  $\mu\text{m}$ , 40  $\mu\text{m}$ , 50  $\mu\text{m}$ , 75  $\mu\text{m}$ , 100  $\mu\text{m}$ , 150  $\mu\text{m}$ , 200  $\mu\text{m}$ ,  
15 250  $\mu\text{m}$ , 300  $\mu\text{m}$ , 400  $\mu\text{m}$ , 500  $\mu\text{m}$ , 750  $\mu\text{m}$ , and 1000  $\mu\text{m}$

Similarly, first elastomeric layer 42 may have a preferred thickness about equal to that of elastomeric layer 20 or 22; second elastomeric layer 46 may have a preferred thickness about equal to that of elastomeric layer 20; and third elastomeric layer 50 may have a preferred thickness about equal to that of elastomeric layer 22.

20

#### Multilayer Soft Lithography Construction Techniques and Materials:

##### **Soft Lithographic Bonding:**

Preferably, elastomeric layers 20 and 22 (or elastomeric layers 42, 46 and 50) are bonded together chemically, using chemistry that is intrinsic to the polymers  
25 comprising the patterned elastomer layers. Most preferably, the bonding comprises two component "addition cure" bonding.

In a preferred aspect, the various layers of elastomer are bound together in a heterogenous bonding in which the layers have a different chemistry. Alternatively, a  
instead. In a fourth aspect, the elastomeric layers may be thermally set elastomers bonded together by heating.

In one aspect of homogeneous bonding, the elastomeric layers are composed of the same elastomer material, with the same chemical entity in one layer reacting with the same chemical entity in the other layer to bond the layers together. In one embodiment, bonding between polymer chains of like elastomer layers may result from activation of a crosslinking agent due to light, heat, or chemical reaction with a separate chemical species.

Alternatively in a heterogeneous aspect, the elastomeric layers are composed of different elastomeric materials, with a first chemical entity in one layer reacting with a second chemical entity in another layer. In one exemplary heterogeneous aspect, the bonding process used to bind respective elastomeric layers together may comprise bonding together two layers of RTV 615 silicone. RTV 615 silicone is a two-part addition-cure silicone rubber. Part A contains vinyl groups and catalyst; part B contains silicon hydride (Si-H) groups. The conventional ratio for RTV 615 is 10A:1B. For bonding, one layer may be made with 30A:1B (i.e. excess vinyl groups) and the other with 3A:1B (i.e. excess Si-H groups). Each layer is cured separately. When the two layers are brought into contact and heated at elevated temperature, they bond irreversibly forming a monolithic elastomeric substrate.

In an exemplary aspect of the present invention, elastomeric structures are formed utilizing Sylgard 182, 184 or 186, or aliphatic urethane diacrylates such as (but not limited to) Ebecryl 270 or Irr 245 from UCB Chemical.

In one embodiment in accordance with the present invention, two-layer elastomeric structures were fabricated from pure acrylated Urethane Ebe 270. A thin bottom layer was spin coated at 8000 rpm for 15 seconds at 170°C. The top and bottom layers were initially cured under ultraviolet light for 10 minutes under nitrogen utilizing a Model ELC 500 device manufactured by Electrolite corporation. The assembled layers were then cured for an additional 30 minutes. Reaction was catalyzed by a 0.5% vol/vol mixture of Irgacure 500 manufactured by Ciba-Geigy Chemicals. The resulting elastomeric material exhibited moderate elasticity and adhesion to glass.

In another embodiment, a two-layer elastomeric structure was fabricated from a thin bottom layer. The thin bottom layer was initially cured for 5 min. and the top layer initially

an additional 30 minutes. Reaction was catalyzed by a 0.5% vol/vol mixture of Irgacure 500 manufactured by Ciba-Geigy Chemicals. The resulting elastomeric material exhibited moderate elasticity and adhered to glass.

Alternatively, other bonding methods may be used, including activating  
5 the elastomer surface, for example by plasma exposure, so that the elastomer layers/substrate will bond when placed in contact. For example, one possible approach to bonding together elastomer layers composed of the same material is set forth by Duffy et al, "Rapid Prototyping of Microfluidic Systems in Poly (dimethylsiloxane)", Analytical Chemistry (1998), 70, 4974-4984, incorporated herein by reference. This paper discusses  
10 that exposing polydimethylsiloxane (PDMS) layers to oxygen plasma causes oxidation of the surface, with irreversible bonding occurring when the two oxidized layers are placed into contact.

Yet another approach to bonding together successive layers of elastomer is to utilize the adhesive properties of uncured elastomer. Specifically, a thin layer of  
15 uncured elastomer such as RTV 615 is applied on top of a first cured elastomeric layer. Next, a second cured elastomeric layer is placed on top of the uncured elastomeric layer. The thin middle layer of uncured elastomer is then cured to produce a monolithic elastomeric structure. Alternatively, uncured elastomer can be applied to the bottom of a first cured elastomer layer, with the first cured elastomer layer placed on top of a second  
20 cured elastomer layer. Curing the middle thin elastomer layer again results in formation of a monolithic elastomeric structure.

Where encapsulation of sacrificial layers is employed to fabricate the elastomer structure as described above in Figs. 8-18, bonding of successive elastomeric layers may be accomplished by pouring uncured elastomer over a previously cured  
25 elastomeric layer and any sacrificial material patterned thereupon. Bonding between elastomer layers occurs due to interpenetration and reaction of the polymer chains of an uncured elastomer layer with the polymer chains of a cured elastomer layer. Subsequent curing of the elastomeric layer will create a bond between the elastomeric layers and

Figure 18 is a cross-sectional view of a microfluidic device showing a first elastomeric layer 1800, a second elastomeric layer 1810, and a sacrificial layer 1820. The first elastomeric layer 1800 is formed by pouring uncured elastomer over a previously cured elastomeric layer and any sacrificial material patterned thereupon. Bonding between elastomer layers occurs due to interpenetration and reaction of the polymer chains of an uncured elastomer layer with the polymer chains of a cured elastomer layer. Subsequent curing of the elastomeric layer will create a bond between the elastomeric layers and

Figure 19 is a cross-sectional view of a microfluidic device showing a first elastomeric layer 1900, a second elastomeric layer 1910, and a sacrificial layer 1920. The first elastomeric layer 1900 is formed by pouring uncured elastomer over a previously cured elastomeric layer and any sacrificial material patterned thereupon. Bonding between elastomer layers occurs due to interpenetration and reaction of the polymer chains of an uncured elastomer layer with the polymer chains of a cured elastomer layer. Subsequent curing of the elastomeric layer will create a bond between the elastomeric layers and

mold 11. Both layers 20 and 22 may be separately baked or cured at about 80°C for 1.5 hours. The second elastomeric layer 22 may be bonded onto first elastomeric layer 20 at about 80°C for about 1.5 hours.

5 Micromachined molds 10 and 12 may be patterned photoresist on silicon wafers. In an exemplary aspect, a Shipley SJR 5740 photoresist was spun at 2000 rpm patterned with a high resolution transparency film as a mask and then developed yielding an inverse channel of approximately 10 microns in height. When baked at approximately 200°C for about 30 minutes, the photoresist reflows and the inverse channels become rounded. In preferred aspects, the molds may be treated with trimethylchlorosilane  
10 (TMCS) vapor for about a minute before each use in order to prevent adhesion of silicone rubber.

Using the various multilayer soft lithography construction techniques and materials set forth herein, the present inventors have experimentally succeeded in creating channel networks comprises of up to seven separate elastomeric layers thick, with each  
15 layer being about 40  $\mu\text{m}$  thick. It is foreseeable that devices comprising more than seven separate elastomeric layers bonded together could be developed.

#### **Suitable Elastomeric Materials:**

Allcock et al, Contemporary Polymer Chemistry, 2<sup>nd</sup> Ed. describes  
20 elastomers in general as polymers existing at a temperature between their glass transition temperature and liquefaction temperature. Elastomeric materials exhibit elastic properties because the polymer chains readily undergo torsional motion to permit uncoiling of the backbone chains in response to a force, with the backbone chains recoiling to assume the prior shape in the absence of the force. In general, elastomers deform when force is  
25 applied, but then return to their original shape when the force is removed. The elasticity exhibited by elastomeric materials may be characterized by a Young's modulus. Elastomeric materials having a Young's modulus of between about 1 Pa - 1 TPa, more preferably between about 10 Pa - 100 GPa, more preferably between about 20 Pa - 1

materials having a Young's modulus outside of these ranges may also be used, depending upon the needs of a particular application.

The systems of the present invention may be fabricated from a wide variety of elastomers. In an exemplary aspect, elastomeric layers 20, 22, 42, 46 and 50 may preferably be fabricated from silicone rubber. However, other suitable elastomers may also be used.

5 In an exemplary aspect of the present invention, the present systems are fabricated from an elastomeric polymer such as GE RTV 615 (formulation), a vinyl-silane crosslinked (type) silicone elastomer (family). However, the present systems are not limited to this one formulation, type or even this family of polymer; rather, nearly any elastomeric polymer is suitable. An important requirement for the preferred method of  
10 fabrication of the present microvalves is the ability to bond multiple layers of elastomers together. In the case of multilayer soft lithography, layers of elastomer are cured separately and then bonded together. This scheme requires that cured layers possess sufficient reactivity to bond together. Either the layers may be of the same type, and are capable of bonding to themselves, or they may be of two different types, and are capable  
15 of bonding to each other. Other possibilities include the use an adhesive between layers and the use of thermoset elastomers.

Given the tremendous diversity of polymer chemistries, precursors, synthetic methods, reaction conditions, and potential additives, there are a huge number of possible elastomer systems that could be used to make monolithic elastomeric  
20 microvalves and pumps. Variations in the materials used will most likely be driven by the need for particular material properties, i.e. solvent resistance, stiffness, gas permeability, or temperature stability.

There are many, many types of elastomeric polymers. A brief description of the most common classes of elastomers is presented here, with the intent of showing  
25 that even with relatively "standard" polymers, many possibilities for bonding exist. Common elastomeric polymers include polyisoprene, polybutadiene, polychloroprene, polyisobutylene, poly(styrene-butadiene-styrene), the polyurethanes, and silicones.

This double bond allows the polymers to be converted to elastomers by

lithography by incomplete vulcanization of the layers to be bonded; photoresist encapsulation would be possible by a similar mechanism.

#### Polyisobutylene:

- 5        Pure polyisobutylene has no double bonds, but is crosslinked to use as an elastomer by including a small amount (~1%) of isoprene in the polymerization. The isoprene monomers give pendant double bonds on the polyisobutylene backbone, which may then be vulcanized as above.

#### 10    Poly(styrene-butadiene-styrene):

- Poly(styrene-butadiene-styrene) is produced by living anionic polymerization (that is, there is no natural chain-terminating step in the reaction), so "live" polymer ends can exist in the cured polymer. This makes it a natural candidate for the present photoresist encapsulation system (where there will be plenty of  
15        unreacted monomer in the liquid layer poured on top of the cured layer). Incomplete curing would allow homogeneous multilayer soft lithography (A to A bonding). The chemistry also facilitates making one layer with extra butadiene ("A") and coupling agent and the other layer ("B") with a butadiene deficit (for *heterogeneous* multilayer soft lithography). SBS is a "thermoset elastomer",  
20        meaning that above a certain temperature it melts and becomes plastic (as opposed to elastic); reducing the temperature yields the elastomer again. Thus, layers can be bonded together by heating.

#### Polyurethanes:

- 25        Polyurethanes are produced from di-isocyanates (A-A) and di-alcohols or di-amines (B-B); since there are a large variety of di-isocyanates and di-alcohols/amines, the number of different types of polyurethanes is huge. The A vs. B nature of the polymers, however, would make them useful for heterogeneous

#### Silicones:





modulus of the cured elastomer. Essentially, the crosslink-capable polymer chains are spread further apart by the addition of "inert" polymer chains, so this is called "dilution". RTV 615 cures at up to 90% dilution, with a dramatic reduction in Young's modulus.

Fig. 49 plots Young's modulus versus percentage dilution with GE SF96-50 diluent of GE RTV 615 elastomer having a ratio of 30:1 A:B. FIG. 49 shows that the flexibility of the elastomer material, and hence the responsiveness of the valve membrane to an applied actuation force, can be controlled during fabrication of the device.

Other examples of doping of elastomer material may include the introduction of electrically conducting or magnetic species, as described in detail below in conjunction with alternative methods of actuating the membrane of the device. Should it be desired, doping with fine particles of material having an index of refraction different than the elastomeric material (i.e. silica, diamond, sapphire) is also contemplated as a system for altering the refractive index of the material. Strongly absorbing or opaque particles may be added to render the elastomer colored or opaque to incident radiation. This may conceivably be beneficial in an optically addressable system.

Finally, by doping the elastomer with specific chemical species, these doped chemical species may be presented at the elastomer surface, thus serving as anchors or starting points for further chemical derivitization.

## 20 Pre-Treatment and Surface Coating

Once the elastomeric material has been molded or etched into the appropriate shape, it may be necessary to pre-treat the material in order to facilitate operation in connection with a particular application.

For example, one possible application for an elastomeric device in accordance with the present invention is to sort biological entities such as cells or DNA. In such an application, the hydrophobic nature of the biological entity may cause it to adhere to the hydrophobic elastomer of the walls of the channel. Therefore, it may be useful to pre-treat the elastomeric structure order to impart a hydrophilic character to the

elastomeric structure. For example, the elastomeric structure may be pre-treated with a hydrophilic coating, such as a silane coating, to impart a hydrophilic character to the elastomeric structure.

Other types of pre-treatment of elastomer material are also contemplated. For example, the elastomeric structure may be pre-treated with a hydrophobic coating, such as a silane coating, to impart a hydrophobic character to the elastomeric structure.

chains), or binding sites for antibodies, as would be advantageous in a given application. Other examples of pre-treatment of elastomer material may include the introduction of reflective material on the elastomer surface, as described in detail below in conjunction with the micro-mirror array application.

5

#### Methods of Operating the Present Invention:

Figs. 7B and 7H together show the closing of a first flow channel by pressurizing a second flow channel, with Fig. 7B (a front sectional view cutting through flow channel 32 in corresponding Fig. 7A), showing an open first flow channel 30; with  
10 Fig. 7H showing first flow channel 30 closed by pressurization of the second flow channel 32.

Referring to Fig. 7B, first flow channel 30 and second flow channel 32 are shown. Membrane 25 separates the flow channels, forming the top of first flow channel 30 and the bottom of second flow channel 32. As can be seen, flow channel 30 is "open".

15 As can be seen in Fig. 7H, pressurization of flow channel 32 (either by gas or liquid introduced therein) causes membrane 25 to deflect downward, thereby pinching off flow F passing through flow channel 30. Accordingly, by varying the pressure in channel 32, a linearly actuatable valving system is provided such that flow channel 30 can be opened or closed by moving membrane 25 as desired. (For illustration purposes only,  
20 channel 30 in Fig. 7G is shown in a "mostly closed" position, rather than a "fully closed" position).

It is to be understood that exactly the same valve opening and closing methods can be achieved with flow channels 60 and 62.

Since such valves are actuated by moving the roof of the channels themselves (i.e.:  
25 moving membrane 25) valves and pumps produced by this technique have a truly zero dead volume, and switching valves made by this technique have a dead volume approximately equal to the active volume of the valve, for example about  $100 \times 100 \times 10 \mu\text{m} = 100\text{pL}$ . Such dead volumes and areas consumed by the moving membrane are approximately two orders of magnitude smaller than for conventional valves and pumps.

nL, 1 fL to 10 nL, 100 fL to 1 nL, and 1 pL to 100 pL

The extremely small dead volume is also achieved by the extremely small

Specifically, the smallest known volumes of fluid capable of being manually metered is around 0.1  $\mu$ l. The smallest known volumes capable of being metered by automated systems is about ten-times larger (1  $\mu$ l). Utilizing pumps and valves in accordance with the present invention, volumes of liquid of 10 nl or smaller can routinely be metered and dispensed. The accurate metering of extremely small volumes of fluid enabled by the present invention would be extremely valuable in a large number of biological applications, including diagnostic tests and assays.

Equation 1 represents a highly simplified mathematical model of deflection of a rectangular, linear, elastic, isotropic plate of uniform thickness by an applied pressure:

$$(1) \quad w = (BPb^4)/(Eh^3), \text{ where:}$$

$w$  = deflection of plate;

$B$  = shape coefficient (dependent upon length vs. width and support of edges of plate);

$P$  = applied pressure;

$b$  = plate width

$E$  = Young's modulus; and

$h$  = plate thickness.

Thus even in this extremely simplified expression, deflection of an elastomeric membrane in response to a pressure will be a function of: the length, width, and thickness of the membrane, the flexibility of the membrane (Young's modulus), and the applied actuation force. Because each of these parameters will vary widely depending upon the actual dimensions and physical composition of a particular elastomeric device in accordance with the present invention, a wide range of membrane thicknesses and elasticities, channel widths, and actuation forces are contemplated by the present invention.

It should be understood that the formula just presented is only an approximation, since in general the membrane does not have uniform thickness, the membrane thickness is not necessarily small compared to the length and width, and the deflection is not necessarily small compared to the thickness of the membrane.

Figs. 21a and 21b illustrate valve opening vs. applied pressure for a 100

of this device was formed by a layer of General Electric Silicones RTV 615 having a thickness of approximately 30 $\mu$ m and a Young's modulus of approximately 750 kPa. Figs. 21a and 21b show the extent of opening of the valve to be substantially linear over most of the range of applied pressures. While the present invention does not require this linear actuation behavior, embodiments of the invention <insert here>.

Air pressure was applied to actuate the membrane of the device through a 10 cm long piece of plastic tubing having an outer diameter of 0.025" connected to a 25 mm piece of stainless steel hypodermic tubing with an outer diameter of 0.025" and an inner diameter of 0.013". This tubing was placed into contact with the control channel by insertion into the elastomeric block in a direction normal to the control channel. Air pressure was applied to the hypodermic tubing from an external LHDA miniature solenoid valve manufactured by Lee Co.

Connection of conventional microfluidic devices to an external fluid flow poses a number of problems avoided by the external configuration just described. One such problem is the fragility of their connections with the external environment. Specifically, conventional microfluidic devices are composed of hard, inflexible materials (such as silicon), to which pipes or tubing allowing connection to external elements must be joined. The rigidity of the conventional material creates significant physical stress at points of contact with small and delicate external tubing, rendering conventional microfluidic devices prone to fracture and leakage at these contact points.

By contrast, the elastomer of the present invention is flexible and can be easily penetrated for external connection by a tube composed a hard material. For example, in an elastomer structure fabricated utilizing the method shown in Figs. 1-7B, a hole extending from the exterior surface of the structure into the control channel can be made by penetrating the elastomer with metal hypodermic tubing after the upper elastomer piece has been removed from the mold (as shown in Fig. 3) and before this piece has been bonded to the lower elastomer piece (as shown in Fig. 4). Between these steps, the roof of the control channel is exposed to the user's view and is accessible to

connection.

Moreover, the elastomer of the present invention will flex in response to

physical connection more robust. This flexibility substantially reduces the chance of leakage or fracture of the present device.

Another disadvantage of conventional microfluidic devices is the difficulty in establishing an effective seal between the device and its external links. Because of the extremely narrow diameter of the channels of these devices, even moderate rates of fluid flow can require extremely high pressures. Unwanted leakage at the junction between the device and external connections may result. However, the flexibility of the elastomer of the present device also aids in overcoming leakage relating to pressure. In particular, the flexible elastomeric material flexes to conform around inserted tubing in order to form a pressure resistant seal.

While control of the flow of material through the device has so far been described utilizing applied gas pressure, other fluids could be used. For example, air is compressible, and thus experiences some finite delay between the time of application of pressure by the external solenoid valve and the time that this pressure is experienced by the membrane. In an alternative embodiment of the present invention, pressure could be applied from an external source to a noncompressible fluid such as water or hydraulic oils, resulting in a near-instantaneous transfer of applied pressure to the membrane. However, if the displaced volume of the valve is large or the control channel is narrow, higher viscosity of a control fluid may contribute to delay in actuation. The optimal medium for transferring pressure will therefore depend upon the particular application and device configuration, and both gaseous and liquid media are contemplated by the invention.

While external applied pressure as described above has been applied by a pump tank system through a pressure regulator and external miniature valve, other methods of applying external pressure are also contemplated in the present invention, including gas tanks, compressors, piston systems, and columns of liquid. Also contemplated is the use of naturally occurring pressure sources such as may be found inside living organisms, such as blood pressure, gastric pressure, the pressure present in

pinch valves, and other types of fluid regulating equipment such as is known in the art.

large portion of its range of travel, with minimal hysteresis. Accordingly, the present valves are ideally suited for microfluidic metering and fluid control. The linearity of the valve response demonstrates that the individual valves are well modeled as Hooke's Law springs. Furthermore, high pressures in the flow channel (i.e.: back pressure) can be countered simply by increasing the actuation pressure. Experimentally, the present inventors have achieved valve closure at back pressures of 70 kPa, but higher pressures are also contemplated. The following is a nonexclusive list of pressure ranges encompassed by the present invention: 10 Pa - 25 MPa; 100 Pa - 10 Mpa, 1 kPa - 1 MPa, 1 kPa - 300 kPa, 5 kPa-200 kPa, and 15 kPa - 100 kPa.

While valves and pumps do not require linear actuation to open and close, linear response does allow valves to more easily be used as metering devices. In one embodiment of the invention, the opening of the valve is used to control flow rate by being partially actuated to a known degree of closure. Linear valve actuation makes it easier to determine the amount of actuation force required to close the valve to a desired degree of closure. Another benefit of linear actuation is that the force required for valve actuation may be easily determined from the pressure in the flow channel. If actuation is linear, increased pressure in the flow channel may be countered by adding the same pressure (force per unit area) to the actuated portion of the valve.

Linearity of a valve depends on the structure, composition, and method of actuation of the valve structure. Furthermore, whether linearity is a desirable characteristic in a valve depends on the application. Therefore, both linearly and non-linearly actuatable valves are contemplated in the present invention, and the pressure ranges over which a valve is linearly actuatable will vary with the specific embodiment.

Fig. 22 illustrates time response (i.e.: closure of valve as a function of time in response to a change in applied pressure) of a  $100\mu\text{m} \times 100\mu\text{m} \times 10\mu\text{m}$  RTV microvalve with 10-cm-long air tubing connected from the chip to a pneumatic valve as described above.

Two periods of digital control signal, actual air pressure at the end of the tubing, and the resulting valve response are shown in Fig. 22. The valve is closed at 100 kPa.

When opening, however, the valve is driven back to its rest position only by its own elasticity. The valve is closed by the actuation pressure, but when the actuation pressure is removed, the valve returns to its rest position only by its own elasticity.

also a lag between the control signal and control pressure response, due to the limitations of the miniature valve used to control the pressure. Calling such lags  $t$  and the time constants  $\tau$ , the values are:  $t_{\text{open}} = 3.63$  ms,  $\tau_{\text{open}} = 1.88$  ms,  $t_{\text{close}} = 2.15$  ms,  $\tau_{\text{close}} = 0.51$  ms. If  $3\tau$  each are allowed for opening and closing, the valve runs comfortably at 75 Hz when filled with aqueous solution.

If one used another actuation method which did not suffer from opening and closing lag, this valve would run at  $\sim 375$  Hz. Note also that the spring constant can be adjusted by changing the membrane thickness; this allows optimization for either fast opening or fast closing. The spring constant could also be adjusted by changing the elasticity (Young's modulus) of the membrane, as is possible by introducing dopant into the membrane or by utilizing a different elastomeric material to serve as the membrane (described above in conjunction with Figs. 7C-7H.)

When experimentally measuring the valve properties as illustrated in Figs. 21 and 22, the valve opening was measured by fluorescence. In these experiments, the flow channel was filled with a solution of fluorescein isothiocyanate (FITC) in buffer (pH  $\geq 8$ ) and the fluorescence of a square area occupying the center  $\sim 1/3$ rd of the channel is monitored on an epi-fluorescence microscope with a photomultiplier tube with a 10 kHz bandwidth. The pressure was monitored with a Wheatstone-bridge pressure sensor (SenSym SCC15GD2) pressurized simultaneously with the control line through nearly identical pneumatic connections.

#### Flow Channel Cross Sections:

The flow channels of the present invention may optionally be designed with different cross sectional sizes and shapes, offering different advantages, depending upon their desired application. For example, the cross sectional shape of the lower flow channel may have a curved upper surface, either along its entire length or in the region disposed under an upper cross channel). Such a curved upper surface facilitates valve sealing, as follows.

As an example, the valve properties of the present invention are illustrated in Fig. 20, the cross-section of a flow channel 30 instead has an upper curved surface.

Referring first to Fig. 19, when flow channel 32 is pressurized, the membrane portion 25 of elastomeric block 24 separating flow channels 30 and 32 will move downwardly to the successive positions shown by the dotted lines 25A, 25B, 25C, 25D, and 25E. As can be seen, incomplete sealing may possibly result at the edges of flow channel 30 adjacent planar substrate 14.

In the alternate preferred embodiment of Fig. 20, flow channel 30a has a curved upper wall 25A. When flow channel 32 is pressurized, membrane portion 25 will move downwardly to the successive positions shown by dotted lines 25A2, 25A3, 25A4 and 25A5, with edge portions of the membrane moving first into the flow channel, followed by top membrane portions. An advantage of having such a curved upper surface at membrane 25A is that a more complete seal will be provided when flow channel 32 is pressurized. Specifically, the upper wall of the flow channel 30 will provide a continuous contacting edge against planar substrate 14, thereby avoiding the "island" of contact seen between wall 25 and the bottom of flow channel 30 in Fig. 19.

Another advantage of having a curved upper flow channel surface at membrane 25A is that the membrane can more readily conform to the shape and volume of the flow channel in response to actuation. Specifically, where a rectangular flow channel is employed, the entire perimeter (2x flow channel height, plus the flow channel width) must be forced into the flow channel. However where an arched flow channel is used, a smaller perimeter of material (only the semi-circular arched portion) must be forced into the channel. In this manner, the membrane requires less change in perimeter for actuation and is therefore more responsive to an applied actuation force to block the flow channel.

In an alternate aspect, (not illustrated), the bottom of flow channel 30 is rounded such that its curved surface mates with the curved upper wall 25A as seen in Fig. 20 described above.

In summary, the actual conformational change experienced by the membrane upon actuation will depend upon the configuration of the particular elastomeric structure. Specifically, the conformational change will depend upon the

material properties of the elastomer used. The conformational change may also depend upon the method of actuation, as actuation of the elastomer by means of a gas applied



pressure will vary somewhat from actuation in response to a magnetic or electrostatic force.

Moreover, the desired conformational change in the membrane will also vary depending upon the particular application for the elastomeric structure. In the simplest embodiments described above, the valve may either be open or closed, with metering to control the degree of closure of the valve. In other embodiments however, it may be desirable to alter the shape of the membrane and/or the flow channel in order to achieve more complex flow regulation. For instance, the flow channel could be provided with raised protrusions beneath the membrane portion, such that upon actuation the membrane shuts off only a percentage of the flow through the flow channel, with the percentage of flow blocked insensitive to the applied actuation force.

Many membrane thickness profiles and flow channel cross-sections are contemplated by the present invention, including rectangular, trapezoidal, circular, ellipsoidal, parabolic, hyperbolic, and polygonal, as well as sections of the above shapes. More complex cross-sectional shapes, such as the embodiment with protrusions discussed immediately above or an embodiment having concavities in the flow channel, are also contemplated by the present invention.

In addition, while the invention is described primarily above in conjunction with an embodiment wherein the walls and ceiling of the flow channel are formed from elastomer, and the floor of the channel is formed from an underlying substrate, the present invention is not limited to this particular orientation. Walls and floors of channels could also be formed in the underlying substrate, with only the ceiling of the flow channel constructed from elastomer. This elastomer flow channel ceiling would project downward into the channel in response to an applied actuation force, thereby controlling the flow of material through the flow channel. In general, monolithic elastomer structures as described elsewhere in the instant application are preferred for microfluidic applications. However, it may be useful to employ channels formed in the substrate where such an arrangement provides advantages. For instance, a substrate

#### Alternate Valve Actuation Techniques:

Electrostatic actuation can be accomplished by forming oppositely charged electrodes (which will tend to attract one another when a voltage differential is applied to them) directly into the monolithic elastomeric structure. For example, referring to Fig. 7B, an optional first electrode 70 (shown in phantom) can be positioned on (or in) membrane 25 and an optional second electrode 72 (also shown in phantom) can be positioned on (or in) planar substrate 14. When electrodes 70 and 72 are charged with opposite polarities, an attractive force between the two electrodes will cause membrane 25 to deflect downwardly, thereby closing the "valve" (i.e.: closing flow channel 30).

For the membrane electrode to be sufficiently conductive to support electrostatic actuation, but not so mechanically stiff so as to impede the valve's motion, a sufficiently flexible electrode must be provided in or over membrane 25. Such an electrode may be provided by a thin metallization layer, doping the polymer with conductive material, or making the surface layer out of a conductive material.

In an exemplary aspect, the electrode present at the deflecting membrane can be provided by a thin metallization layer which can be provided, for example, by sputtering a thin layer of metal such as 20 nm of gold. In addition to the formation of a metallized membrane by sputtering, other metallization approaches such as chemical epitaxy, evaporation, electroplating, and electroless plating are also available. Physical transfer of a metal layer to the surface of the elastomer is also available, for example by evaporating a metal onto a flat substrate to which it adheres poorly, and then placing the elastomer onto the metal and peeling the metal off of the substrate.

A conductive electrode 70 may also be formed by depositing carbon black (i.e. Cabot Vulcan XC72R) on the elastomer surface, either by wiping on the dry powder or by exposing the elastomer to a suspension of carbon black in a solvent which causes swelling of the elastomer, (such as a chlorinated solvent in the case of PDMS). Alternatively, the electrode 70 may be formed by constructing the entire layer 20 out of elastomer doped with conductive material (i.e. carbon black or finely divided metal particles). Yet further alternatively, the electrode may be formed by electrostatic

actuation of the valve, the valve is not required to move, may be either a compliant electrode as described above, or a

conventional electrode such as evaporated gold, a metal plate, or a doped semiconductor electrode.

Alternatively, magnetic actuation of the flow channels can be achieved by fabricating the membrane separating the flow channels with a magnetically polarizable material such as iron, or a permanently magnetized material such as polarized NdFeB. In experiments conducted by the present inventors, magnetic silicone was created by the addition of iron powder (about 1  $\mu\text{m}$  particle size), up to 20% iron by weight.

Where the membrane is fabricated with a magnetically polarizable material, the membrane can be actuated by attraction in response to an applied magnetic field. Where the membrane is fabricated with a material capable of maintaining permanent magnetization, the material can first be magnetized by exposure to a sufficiently high magnetic field, and then actuated either by attraction or repulsion in response to the polarity of an applied inhomogenous magnetic field.

The magnetic field causing actuation of the membrane can be generated in a variety of ways. In one embodiment, the magnetic field is generated by an extremely small inductive coil formed in or proximate to the elastomer membrane. The actuation effect of such a magnetic coil would be localized, allowing actuation of individual pump and/or valve structures. Alternatively, the magnetic field could be generated by a larger, more powerful source, in which case actuation would be global and would actuate multiple pump and/or valve structures at one time.

It is further possible to combine pressure actuation with electrostatic or magnetic actuation. Specifically, a bellows structure in fluid communication with a recess could be electrostatically or magnetically actuated to change the pressure in the recess and thereby actuate a membrane structure adjacent to the recess.

In addition to electrical or magnetic actuation as described above, optional electrolytic and electrokinetic actuation systems are also contemplated by the present invention. For example, actuation pressure on the membrane could arise from an electrolytic reaction in a recess overlying the membrane. In such an embodiment,

the recess could be filled with an electrolyte and a conductive electrode could be placed in the recess.

Alternatively, the recess could be filled with an electrolyte and a conductive electrode could be placed in the recess.

Alternatively, actuation pressure on the membrane could arise from an electrokinetic effect. For example, the recess could be filled with an electrolyte and a conductive electrode could be placed in the recess.

an electrolyte present in the control channel. Migration of charged species in the electrolyte to the respective electrodes could give rise to a pressure differential.

Finally, it is also possible to actuate the device by causing a fluid flow in the control channel based upon the application of thermal energy, either by thermal expansion or by production of gas from liquid. Similarly, chemical reactions generating gaseous products may produce an increase in pressure sufficient for membrane actuation.

#### Networked Systems:

Figs. 23A and 23B show a views of a single on/off valve, identical to the systems set forth above, (for example in Fig. 7A). Figs. 24A and 24B shows a peristaltic pumping system comprised of a plurality of the single addressable on/off valves as seen in Fig. 23, but networked together. Fig. 25 is a graph showing experimentally achieved pumping rates vs. frequency for the peristaltic pumping system of Fig. 24. Figs. 26A and 26B show a schematic view of a plurality of flow channels which are controllable by a single control line. This system is also comprised of a plurality of the single addressable on/off valves of Fig. 23, multiplexed together, but in a different arrangement than that of Fig. 23. Fig. 27 is a schematic illustration of a multiplexing system adapted to permit fluid flow through selected channels, comprised of a plurality of the single on/off valves of Fig. 23, joined or networked together.

Referring first to Figs. 23A and 23B, a schematic of flow channels 30 and 32 is shown. Flow channel 30 preferably has a fluid (or gas) flow F passing therethrough. Flow channel 32, (which crosses over flow channel 30, as was already explained herein), is pressurized such that membrane 25 separating the flow channels may be depressed into the path of flow channel 30, shutting off the passage of flow F therethrough, as has been explained. As such, "flow channel" 32 can also be referred to as a "control line" which actuates a single valve in flow channel 30. In Figs. 23 to 26, a plurality of such addressable valves are joined or networked together in various arrangements to produce pumps, capable of peristaltic pumping, and other fluidic logic applications.

FIG. 23A is a schematic view of a single addressable on/off valve.

FIG. 23B is a schematic view of a single addressable on/off valve, similar to FIG. 23A, flow F through flow channel 30 is shut off under membrane 25A at the intersection

FIG. 24A is a schematic view of a peristaltic pumping system comprised of a plurality of the single addressable on/off valves of FIG. 23.

control line 32B, flow F through flow channel 30 is shut off under membrane 25B at the intersection of control line 32B and flow channel 30, etc.

Each of control lines 32A, 32B, and 32C is separately addressable. Therefore, peristalsis may be actuated by the pattern of actuating 32A and 32C together, followed by 32A, followed by 32A and 32B together, followed by 32B, followed by 32B and C together, etc. This corresponds to a successive "101, 100, 110, 010, 011, 001" pattern, where "0" indicates "valve open" and "1" indicates "valve closed." This peristaltic pattern is also known as a 120° pattern (referring to the phase angle of actuation between three valves). Other peristaltic patterns are equally possible, including 60° and 90° patterns.

In experiments performed by the inventors, a pumping rate of 2.35  $\mu\text{L/s}$  was measured by measuring the distance traveled by a column of water in thin (0.5 mm i.d.) tubing; with 100x100x10  $\mu\text{m}$  valves under an actuation pressure of 40 kPa. The pumping rate increased with actuation frequency until approximately 75 Hz, and then was nearly constant until above 200 Hz. The valves and pumps are also quite durable and the elastomer membrane, control channels, or bond have never been observed to fail. In experiments performed by the inventors, none of the valves in the peristaltic pump described herein show any sign of wear or fatigue after more than 4 million actuations. In addition to their durability, they are also gentle. A solution of *E. Coli* pumped through a channel and tested for viability showed a 94% survival rate.

Fig. 25 is a graph showing experimentally achieved pumping rates vs. frequency for the peristaltic pumping system of Fig. 24.

Figs. 26A and 26B illustrates another way of assembling a plurality of the addressable valves of Fig. 21. Specifically, a plurality of parallel flow channels 30A, 30B, and 30C are provided. Flow channel (i.e.: control line) 32 passes thereover across flow channels 30A, 30B, and 30C. Pressurization of control line 32 simultaneously shuts off flows F1, F2 and F3 by depressing membranes 25A, 25B, and 25C located at the intersections of control line 32 and flow channels 30A, 30B, and 30C.

detection of membrane separating the respective flow channels, and/or the flow passing thereabove (for example, membranes 25A, 25B, and 25C in Figs. 26A and 26B)

flow channel control line 32 in Figs. 26A and 26B, it is possible to have a control line pass over multiple flow channels, yet only actuate (i.e.: seal) desired flow channels. Fig. 27 illustrates a schematic of such a system, as follows.

A plurality of parallel flow channels 30A, 30B, 30C, 30D, 30E and 30F are positioned under a plurality of parallel control lines 32A, 32B, 32C, 32D, 32E and 32F. Control channels 32A, 32B, 32C, 32D, 32E and 32F are adapted to shut off fluid flows F1, F2, F3, F4, F5 and F6 passing through parallel flow channels 30A, 30B, 30C, 30D, 30E and 30F using any of the valving systems described above, with the following modification.

Each of control lines 32A, 32B, 32C, 32D, 32E and 32F have both wide and narrow portions. For example, control line 32A is wide in locations disposed over flow channels 30A, 30C and 30E. Similarly, control line 32B is wide in locations disposed over flow channels 30B, 30D and 30F, and control line 32C is wide in locations disposed over flow channels 30A, 30B, 30E and 30F.

At the locations where the respective control line is wide, its pressurization will cause the membrane (25) separating the flow channel and the control line to depress significantly into the flow channel, thereby blocking the flow passage therethrough. Conversely, in the locations where the respective control line is narrow, membrane (25) will also be narrow. Accordingly, the same degree of pressurization will not result in membrane (25) becoming depressed into the flow channel (30). Therefore, fluid passage thereunder will not be blocked.

For example, when control line 32A is pressurized, it will block flows F1, F3 and F5 in flow channels 30A, 30C and 30E. Similarly, when control line 32C is pressurized, it will block flows F1, F2, F5 and F6 in flow channels 30A, 30B, 30E and 30F. As can be appreciated, more than one control line can be actuated at the same time. For example, control lines 32A and 32C can be pressurized simultaneously to block all fluid flow except F4 (with 32A blocking F1, F3 and F5; and 32C blocking F1, F2, F5 and F6).

FIG. 27 is a schematic diagram of a system for selectively actuating one or more of a plurality of parallel flow channels (30) using a plurality of parallel control lines (32). The system includes a plurality of parallel flow channels (30) and a plurality of parallel control lines (32) positioned over the flow channels (30). The control lines (32) are adapted to selectively actuate one or more of the flow channels (30) by pressurizing the control lines (32) at specific locations. The system is configured such that the control lines (32) are wide in locations disposed over the flow channels (30) to be actuated, and narrow in locations disposed over the flow channels (30) not to be actuated. By varying the positioning of the wide and narrow portions of the control lines (32), the system can selectively actuate any combination of the flow channels (30).

property of such systems is that it is possible to turn on any one flow channel out of  $n$  flow channels with only  $2(\log_2 n)$  control lines.

The inventors have succeeded in fabricating microfluidic structures with densities of 30 devices /mm<sup>2</sup>, but greater densities are achievable.

5

#### Selectively Addressable Reaction Chambers Along Flow Lines:

In a further embodiment of the invention, illustrated in Figs. 28A, 28B, 28C and 28D, a system for selectively directing fluid flow into one more of a plurality of reaction chambers disposed along a flow line is provided.

10

Fig. 28A shows a top view of a flow channel 30 having a plurality of reaction chambers 80A and 80B disposed therealong. Preferably flow channel 30 and reaction chambers 80A and 80B are formed together as recesses into the bottom surface of a first layer 100 of elastomer.

15

Fig. 28B shows a bottom plan view of another elastomeric layer 110 with two control lines 32A and 32B each being generally narrow, but having wide extending portions 33A and 33B formed as recesses therein.

20

As seen in the exploded view of Fig. 28C, and assembled view of Fig. 28D, elastomeric layer 110 is placed over elastomeric layer 100. Layers 100 and 110 are then bonded together, and the integrated system operates to selectively direct fluid flow F (through flow channel 30) into either or both of reaction chambers 80A and 80B, as follows. Pressurization of control line 32A will cause the membrane 25 (i.e.: the thin portion of elastomer layer 100 located below extending portion 33A and over regions 82A of reaction chamber 80A) to become depressed, thereby shutting off fluid flow passage in regions 82A, effectively sealing reaction chamber 80 from flow channel 30. As can also be seen, extending portion 33A is wider than the remainder of control line 32A. As such, pressurization of control line 32A will not result in control line 32A sealing flow channel 30.

25

As can be appreciated, either or both of control lines 32A and 32B can be pressurized together, sample

addressable reaction chambers disposed along a flow line (Figs. 28) can be combined with a system for selectively directing fluid flow into one more of a plurality of

can be sent to any particular reaction chamber in an array of reaction chambers. An example of such a system is provided in Fig. 29, in which parallel control channels 32A, 32B and 32C with extending portions 34 (all shown in phantom) selectively direct fluid flows F1 and F2 into any of the array of reaction wells 80A, 80B, 80C or 80D as explained above; while pressurization of control lines 32C and 32D selectively shuts off flows F2 and F1, respectively.

In yet another novel embodiment, fluid passage between parallel flow channels is possible. Referring to Fig. 30, either or both of control lines 32A or 32D can be depressurized such that fluid flow through lateral passageways 35 (between parallel flow channels 30A and 30B) is permitted. In this aspect of the invention, pressurization of control lines 32C and 32D would shut flow channel 30A between 35A and 35B, and would also shut lateral passageways 35B. As such, flow entering as flow F1 would sequentially travel through 30A, 35A and leave 30B as flow F4.

#### Switchable Flow Arrays

In yet another novel embodiment, fluid passage can be selectively directed to flow in either of two perpendicular directions. An example of such a "switchable flow array" system is provided in Figs. 31A to 31D. Fig. 31A shows a bottom view of a first layer of elastomer 90, (or any other suitable substrate), having a bottom surface with a pattern of recesses forming a flow channel grid defined by an array of solid posts 92, each having flow channels passing therearound.

In preferred aspects, an additional layer of elastomer is bound to the top surface of layer 90 such that fluid flow can be selectively directed to move either in direction F1, or perpendicular direction F2. Fig. 31 is a bottom view of the bottom surface of the second layer of elastomer 95 showing recesses formed in the shape of alternating "vertical" control lines 96 and "horizontal" control lines 94. "Vertical" control lines 96 have the same width therealong, whereas "horizontal" control lines 94 have alternating wide and narrow portions, as shown.

Elastomeric layer 95 is positioned over top of elastomeric layer 90 such

shown in Fig. 31D.

As shown in Fig. 31C, each "horizontal" control line 94 has



initially positioned between layers 90 and 95 in regions 98 will be deflected downwardly over the array of flow channels such that flow is only able to pass in flow direction F2 (i.e.: vertically), as shown.

5 As can be seen in Fig. 31D, when "horizontal" control lines 94 are pressurized, the membrane of the integrated structure formed by the elastomeric layer initially positioned between layers 90 and 95 in regions 99 will be deflected downwardly over the array of flow channels, (but only in the regions where they are widest), such that flow is only able to pass in flow direction F1 (i.e.: horizontally), as shown.

10 The design illustrated in Figs. 31 allows a switchable flow array to be constructed from only two elastomeric layers, with no vertical vias passing between control lines in different elastomeric layers required. If all vertical flow control lines 94 are connected, they may be pressurized from one input. The same is true for all horizontal flow control lines 96.

### 15 Biopolymer Synthesis

The present elastomeric valving structures can also be used in biopolymer synthesis, for example, in synthesizing oligonucleotides, proteins, peptides, DNA, etc. In a preferred aspect, such biopolymer synthesis systems may comprise an integrated system comprising an array of reservoirs, fluidic logic (according to the present invention) for  
20 selecting flow from a particular reservoir, an array of channels or reservoirs in which synthesis is performed, and fluidic logic (also according to the present invention) for determining into which channels the selected reagent flows. An example of such a system 200 is illustrated in Fig. 32, as follows.

25 Four reservoirs 150A, 150B, 150C and 150D have bases A, C, T and G respectively disposed therein, as shown. Four flow channels 30A, 30B, 30C and 30D are connected to reservoirs 150A, 150B, 150C and 150D. Four control lines 32A, 32B, 32C and 32D (shown in phantom) are disposed thereacross with control line 32A permitting flow only through flow channel 30A (i.e.: sealing flow channels 30B, 30C and 30D).

When control line 32A is pressurized, fluid from reservoir 150A flows into flow channel 30A.

30 The fluid then passes through flow channel 30A to a junction 125. From junction 125, the fluid can pass through flow channel 120 to a reservoir 122, or through flow channel 121 to a reservoir 123, or through flow channel 124 to a reservoir 125. The fluid can also pass

a plurality of synthesis channels or chambers 122A, 122B, 122C, 122D or 122E in which solid phase synthesis may be carried out.

Fig. 33 shows a further extension of this system on which a plurality of reservoirs R1 to R13 (which may contain bases A, T, C and G, or any other reactants, such as would be used in combinatorial chemistry), are connected to systems 200 as set forth in Figs. 32. Systems 200 are connected to a multiplexed channel flow controller 125, (including, for example, any system as shown in Figs. 26A to 31D) which is in turn connected to a switchable flow array (for example as shown in Figs. 31). An advantage of this system is that both of multiplexed channel flow controllers 125 and fluid selection systems 200 can be controlled by the same pressure inputs 170 and 172, provided a "close horizontal" and a "close vertical" control lines (160 and 162, in phantom) are also provided.

In further alternate aspects of the invention, a plurality of multiplexed channel flow controllers (such as 125) may be used, with each flow controller initially positioned stacked above one another on a different elastomeric layer, with vertical vias or interconnects between the elastomer layers (which may be created by lithographically patterning an etch resistant layer on top of a elastomer layer, then etching the elastomer and finally removing the etch resist before adding the last layer of elastomer).

For example, a vertical via in an elastomer layer can be created by etching a hole down onto a raised line on a micromachined mold, and bonding the next layer such that a channel passes over that hole. In this aspect of the invention, multiple synthesis with a plurality of multiplexed channel flow controllers 125 is possible.

The bonding of successive layers of molded elastomer to form a multi-layer structure is shown in Fig. 34, which is an optical micrograph of a section of a test structure composed of seven layers of elastomer. The scale bar of Fig. 34 is 200  $\mu\text{m}$ .

One method for fabricating an elastomer layer having the vertical via feature utilized in a multi-layer structure is shown in FIGS. 35A-35D. FIG. 35A shows formation of elastomer layer 3500 over micromachined mold 3502 including raised line

blocking layer 3504 to cover masked regions 3508 and leave exposed unmasked regions

3510. FIG. 35C shows the exposure to solvent which removes etch blocking layer 3504 in unmasked regions 3510.

FIG. 35D shows removal of the patterned photoresist, followed by subsequent etching of underlying elastomer 3500 in unmasked regions 3510 to form vertical via 3512. Subsequent exposure to solvent removes remaining etch blocking layer 3504 in masked regions 3508 selective to the surrounding elastomer 3500 and mold 3502. This elastomer layer may then be incorporated into an elastomer structure by multilayer soft lithography.

This series of steps can be repeated as necessary to form a multi-layered structure having the desired number and orientation of vertical vias between channels of successive elastomer layers.

The inventors of the present invention have succeeded in etching vias through GE RTV 615 layers using a solution of Tetrabutylammonium fluoride in organic solvent. Gold serves as the etch blocking material, with gold removed selective to GE RTV 615 utilizing a KI/I<sub>2</sub>/H<sub>2</sub>O mixture.

Alternatively, vertical vias between channels in successive elastomer layers could be formed utilizing a negative mask technique. In this approach, a negative mask of a metal foil is patterned, and subsequent formation of an etch blocking layer is inhibited where the metal foil is present. Once the etch blocking material is patterned, the negative metal foil mask is removed, permitting selective etching of the elastomer as described above.

In yet another approach, vertical vias could be formed in an elastomer layer using ablation of elastomer material through application of radiation from an applied laser beam.

While the above approach is described in connection with the synthesis of biopolymers, the invention is not limited to this application. The present invention could also function in a wide variety of combinatorial chemical synthesis approaches.

limited to any particular application or use thereof. In preferred aspects, the following

## 1. Cell/DNA Sorting

The present microfluidic pumps and valves can also be used in flow cytometers for cell sorting and DNA sizing. Sorting of objects based upon size is extremely useful in many technical fields.

5 For example, many assays in biology require determination of the size of molecular-sized entities. Of particular importance is the measurement of length distribution of DNA molecules in a heterogeneous solution. This is commonly done using gel electrophoresis, in which the molecules are separated by their differing mobility in a gel matrix in an applied electric field, and their positions detected by absorption or  
10 emission of radiation. The lengths of the DNA molecules are then inferred from their mobility.

While powerful, electrophoretic methods pose disadvantages. For medium to large DNA molecules, resolution, i.e. the minimum length difference at which different molecular lengths may be distinguished, is limited to approximately 10% of the total  
15 length. For extremely large DNA molecules, the conventional sorting procedure is not workable. Moreover, gel electrophoresis is a relatively lengthy procedure, and may require on the order of hours or days to perform.

The sorting of cellular-sized entities is also an important task. Conventional flow cell sorters are designed to have a flow chamber with a nozzle and are  
20 based on the principle of hydrodynamic focusing with sheath flow. Most conventional cell sorters combine the technology of piezo-electric drop generation and electrostatic deflection to achieve droplet generation and high sorting rates. However, this approach offers some important disadvantages. One disadvantage is that the complexity, size, and expense of the sorting device requires that it be reusable in order to be cost-effective.  
25 Reuse can in turn lead to problems with residual materials causing contamination of samples and turbulent fluid flow.

Therefore, there is a need in the art for a simple, inexpensive, and easily fabricated sorting device which relies upon the mechanical control of fluid flow rather

than the use of piezo-electric or electrostatic deflection.

FIG. 1 is a schematic diagram of a microfluidic device 100. The device 100 includes a flow channel 102 formed in an elastomeric block 104. Specifically, flow channel 102 is T-shaped and is formed by a first channel 102a and a second channel 102b. The first channel 102a is in fluid communication with a sample inlet 106, and the second channel 102b is in fluid communication with a sample inlet 108.

(square, circle, triangle, etc.). Left branch 3602b of flow channel 3602 is in fluid communication with waste reservoir 3608. Right branch 3602c of flow channel 3602 is in communication with collection reservoir 3610.

5 Control channels 3612a, 3612b, and 3612c overlie and are separated from stem 3602a of flow channel 3602 by elastomeric membrane portions 3614a, 3614b, and 3614c respectively. Together, stem 3602a of flow channel 3602 and control channels 3612a, 3612b, and 3612c form first peristaltic pump structure 3616 similar to that described at length above in connection with FIG. 24a.

10 Control channel 3612d overlies and is separated from right branch 3602c of flow channel 3602 by elastomeric membrane portion 3614d. Together, right branch 3602c of flow channel 3602 and control channels 3612d forms first valve structure 3618a. Control channel 3612e overlies and is separated from left branch 3602c of flow channel 3602 by elastomeric membrane portion 3614e. Together, left branch 3602c of flow channel 3602 and control channel 3612e forms second valve structure 3618b.

15 As shown in FIG. 36, stem 3602a of flow channel 3602 narrows considerably as it approaches detection window 3620 adjacent to the junction of stem 3602a, right branch 3602b, and left branch 3602c. Detection window 3620 is of sufficient width to allow for uniform illumination of this region. In one embodiment, the width of the stem narrows from 100  $\mu\text{m}$  to 5  $\mu\text{m}$  at the detection window. The width of  
20 the stem at the detection window can be precisely formed using the soft lithography or photoresist encapsulation fabrication techniques described extensively above, and will be depend upon the nature and size of the entity to be sorted.

Operation of sorting device in accordance with one embodiment of the present invention is as follows.

25 The sample is diluted to a level such that only a single sortable entity would be expected to be present in the detection window at any time. Peristaltic pump 3616 is activated by flowing a fluid through control channels 3612a-c as described extensively above. In addition, second valve structure 3618b is closed by flowing fluid through control channel 3612e. As a result, the flow of sample fluid is directed through

narrows of stem 3604, sortable entities present in sample reservoir 3604 are carried by the flow of sample fluid through the narrow stem 3604 to the detection window 3620.

Radiation 3640 from source 3642 is introduced into detection window 3620. This is possible due to the transmissive property of the elastomeric material. Absorption or emission of radiation 3640 by sortable entity 3606 is then detected by detector 3644.

5           If sortable entity 3606a within detection window 3620 is intended to be segregated and collected by sorting device 3600, first valve 3618a is activated and second valve 3618b is deactivated. This has the effect of drawing sortable entity 3606a into collection reservoir 3610, and at the same time transferring second sortable entity 3606b into detection window 3620. If second sortable entity 3602b is also identified for  
10 collection, peristaltic pump 3616 continues to flow fluid through right branch 3602c of flow channel 3602 into collection reservoir 3610. However, if second entity 3606b is not to be collected, first valve 3618a opens and second valve 3618b closes, and first peristaltic pump 3616 resumes pumping liquid through left branch 3602b of flow channel 3602 into waste reservoir 3608.

15           While one specific embodiment of a sorting device and a method for operation thereof is described in connection with FIG. 36, the present invention is not limited to this embodiment. For example, fluid need not be flowed through the flow channels using the peristaltic pump structure, but could instead be flowed under pressure with the elastomeric valves merely controlling the directionality of flow. In yet another  
20 embodiment, a plurality of sorting structures could be assembled in series in order to perform successive sorting operations, with the waste reservoir of FIG. 36 simply replaced by the stem of the next sorting structure.

          Moreover, a high throughput method of sorting could be employed, wherein a continuous flow of fluid from the sample reservoir through the window and  
25 junction into the waste reservoir is maintained until an entity intended for collection is detected in the window. Upon detection of an entity to be collected, the direction of fluid flow by the pump structure is temporarily reversed in order to transport the desired particle back through the junction into the collection reservoir. In this manner, the sorting

device can be used to sort a large number of entities, such as cells, molecules, or biological entities.

*Sorting in accordance with the present invention*

          Sorting in accordance with the present invention would avoid the problems associated with the prior art sorting devices, such as the need to

the solution and surface chemistry effects, a differential mobility of different chemical species, and decreased viability of living organisms in the mobile medium.

## 2. Semiconductor Processing

5           Systems for semiconductor gas flow control, (particularly for epitaxial applications in which small quantities of gases are accurately metered), are also contemplated by the present invention. For example, during fabrication of semiconductor devices solid material is deposited on top of a semiconductor substrate utilizing chemical vapor deposition (CVD). This is accomplished by exposing the substrate to a mixture of  
10       gas precursor materials, such that these gases react and the resulting product crystallizes on top of the substrate.

          During such CVD processes, conditions must be carefully controlled to ensure uniform deposition of material free of defects that could degrade the operation of the electrical device. One possible source of nonuniformity is variation in the flow rate of  
15       reactant gases to the region over the substrate. Poor control of the gas flow rate can also lead to variations in the layer thicknesses from run to run, which is another source of error. Unfortunately, there has been a significant problem in controlling the amount of gas flowed into the processing chamber, and maintaining stable flow rates in conventional gas delivery systems.

20           Accordingly, FIG. 37A shows one embodiment of the present invention adapted to convey, at precisely-controllable flow rates, processing gas over the surface of a semiconductor wafer during a CVD process. Specifically, semiconductor wafer 3700 is positioned upon wafer support 3702 located within a CVD chamber. Elastomeric structure 3704 containing a large number of evenly distributed orifices 3706 is positioned  
25       just above the surface of wafer 3700.

          A variety of process gases are flowed at carefully controlled rates from reservoirs 3708a and 3708b, through flow channels in elastomeric block 3704, and out of orifices 3706. As a result of the precisely controlled flow of process gases above wafer 3700, a solid material 3710 having an extremely uniform structure is deposited

          flowed through valves that respond in a linear fashion to an applied actuation pressure, as shown in FIG. 37B and 37C, and in FIGS. 37A and 37B. Alternatively, or in addition to

accordance with the present invention can be used to precisely meter process gas flow.

In addition to the chemical vapor deposition processes described above, the present technique is also useful to control gas flow in techniques such as molecular beam epitaxy and reactive ion etching.

5

### 3. Micro Mirror Arrays

While the embodiments of the present invention described thus far relate to operation of a structure composed entirely of elastomeric material, the present invention is not limited to this type of structure. Specifically, it is within the scope of the present invention to combine an elastomeric structure with a conventional, silicon-based semiconductor structure.

For example, further contemplated uses of the present microfabricated pumps and valves are in optical displays in which the membrane in an elastomeric structure reflects light either as a flat planar or as a curved surface depending upon whether the membrane is activated. As such, the membrane acts as a switchable pixel. An array of such switchable pixels, with appropriate control circuitry, could be employed as a digital or analog micro mirror array.

Accordingly, FIG. 38 shows an exploded view of a portion of one embodiment of a micro mirror array in accordance with the present invention.

20 Micro mirror array 3800 includes first elastomer layer 3802 overlying and separated from and underlying semiconductor structure 3804 by second elastomer layer 3806. Surface 3804a of semiconductor structure 3804 bears a plurality of electrodes 3810. Electrodes 3810 are individually addressable through conducting row and column lines, as would be known to one of ordinary skill in the art.

25 First elastomeric layer 3802 includes a plurality of intersecting channels 3822 underlying an electrically conducting, reflecting elastomeric membrane portion 3802a. First elastomeric layer 3802 is aligned over second elastomeric layer 3806 and underlying semiconductor device 3804 such that points of intersection of channels 3822

are positioned over electrodes 3810.

FIG. 38 is a schematic diagram of a micro mirror array 3800 in accordance with the present invention. The array 3800 is formed by depositing an elastomeric material onto a mold featuring intersecting channels, curing the elastomer, removing the elastomer from the mold, and then depositing a conductive material into the channels.



Figs. 7C-7G above, first elastomeric layer 3822 may be formed from two layers of elastomer by inserting elastomeric material into a mold containing intersecting channels such that the elastomeric material is flush with the height of the channel walls, and then bonding a separate doped elastomer layer to the existing elastomeric material to form a  
5 membrane on the top surface.

Alternatively, the first elastomeric layer 3802 may be produced from electrically conductive elastomer, where the electrical conductivity is due either to doping or to the intrinsic properties of the elastomer material.

During operation of reflecting structure 3800, electrical signals are  
10 communicated along a selected row line and column line to electrode 3810a. Application of voltage to electrode 3810a generates an attractive force between electrode 3810a and overlying membrane 3802a. This attractive force actuates a portion of membrane 3802a, causing this membrane portion to flex downward into the cavity resulting from intersection of the channels 3822. As a result of distortion of membrane 3802a from  
15 planar to concave, light is reflected differently at this point in the surface of elastomer structure 3802 than from the surrounding planar membrane surface. A pixel image is thereby created.

The appearance of this pixel image is variable, and may be controlled by altering the magnitude of voltage applied to the electrode. A higher voltage applied to the  
20 electrode will increase the attractive force on the membrane portion, causing further distortion in its shape. A lower voltage applied to the electrode will decrease the attractive force on the membrane, reducing distortion in its shape from the planar. Either of these changes will affect the appearance of the resulting pixel image.

A variable micro mirror array structure as described could be used in a  
25 variety of applications, including the display of images. Another application for a variable micro mirror array structure in accordance with an embodiment of the present invention would be as a high capacity switch for a fiber optics communications system, with each pixel capable of affecting the reflection and transfer of a component of an

invention is not limited to this particular embodiment.

#### 4. Refracting Structures

The micro-mirror array structure just described controls reflection of incident light. However, the present invention is not limited to controlling reflection. Yet another embodiment of the present invention enables the exercise of precise control over refraction of incident light in order to create lens and filter structures.

FIG. 39 shows one embodiment of a refractive structure in accordance with the present invention. Refractive structure 3900 includes first elastomeric layer 3902 and second elastomeric layer 3904 composed of elastomeric material capable of transmitting incident light 3906.

First elastomeric layer 3902 has convex portion 3902a which may be created by curing elastomeric material formed over a micromachined mold having a concave portion. Second elastomeric layer 3904 has a flow channel 3905 and may be created from a micromachined mold having a raised line as discussed extensively above.

First elastomer layer 3902 is bonded to second elastomer layer 3904 such that convex portion 3902a is positioned above flow channel 3905. This structure can serve a variety of purposes.

For example, light incident to elastomeric structure 3900 would be focused into the underlying flow channel, allowing the possible conduction of light through the flow channel. Alternatively, in one embodiment of an elastomeric device in accordance with the present invention, fluorescent or phosphorescent liquid could be flowed through the flow channel, with the resulting light from the fluid refracted by the curved surface to form a display.

FIG. 40 shows another embodiment of a refractive structure in accordance with the present invention. Refractive structure 4000 is a multilayer optical train based upon a Fresnel lens design. Specifically, refractive structure 4000 is composed of four successive elastomer layers 4002, 4004, 4006, and 4008, bonded together. The upper surfaces of each of first, second, and third elastomer layers 4002, 4004, and 4006 bear uniform serrations 4010 regularly spaced by a distance X that is much larger than the

thickness of the elastomer layers. Serrations 4010 are used to focus the incident light, and as would be understood of one of ordinary skill in the art.

FIG. 41 shows another embodiment of a refractive structure in accordance with the present invention.

are also spaced apart by a much smaller distance  $Y$  than the serrations of the overlying elastomeric layers, with  $Y$  on the order of the wavelength of incident light, such that elastomeric layer 4008 functions as a diffraction grating.

FIG. 41 illustrates an embodiment of a refractive structure in accordance with the present invention which utilizes difference in material refractive index to primarily accomplish diffraction. Refractive structure 4100 includes lower elastomeric portion 4102 covered by upper elastomeric portion 4104. Both lower elastomeric portion 4102 and upper elastomeric portion 4104 are composed of material transmitting incident light 4106. Lower elastomeric portion 4102 includes a plurality of serpentine flow channels 4108 separated by elastomeric lands 4110. Flow channels 4108 include fluid 4112 having a different refractive index than the elastomeric material making up lands 4110. Fluid 4112 is pumped through serpentine flow channels 4108 by the operation of pump structure 4114 made up of parallel control channels 4116a and 4116b overlying and separated from inlet portion 4108a of flow channel 4108 by moveable membrane 4118.

Light 4106 incident to refractive structure 4100 encounters a series of uniformly-spaced fluid-filled flow channels 4108 separated by elastomeric lands 4110. As a result of the differing optical properties of material present in these respective fluid/elastomer regions, portions of the incident light are not uniformly refracted and interact to form an interference pattern. A stack of refractive structures of the manner just described can accomplish even more complex and specialized refraction of incident light.

The refractive elastomeric structures just described can fulfill a variety of purposes. For example, the elastomeric structure could act as a filter or optical switch to block selected wavelengths of incident light. Moreover, the refractive properties of the structure could be readily adjusted depending upon the needs of a particular application.

For example, the composition (and hence refractive index) of fluid flowed through the flow channels could be changed to affect diffraction. Alternatively, or in conjunction with changing the identity of the fluid flowed, the distance separating adjacent flow channels can be precisely controlled during fabrication of the structure in order to accomplish a particular refraction pattern having the desired characteristics.

#### Normally-Closed Valve Structure

FIGS. 7B and 7H above depict a valve structure in which the elastomeric membrane 708 is in a normally-closed position and actuated position in

which the flow channel is blocked. However, the present invention is not limited to this particular valve configuration.

FIGS. 42A-42J show a variety of views of a normally-closed valve structure in which the elastomeric membrane is moveable from a first relaxed position blocking a flow channel, to a second actuated position in which the flow channel is open, utilizing a negative control pressure.

FIG. 42A shows a plan view, and FIG. 42B shows a cross sectional view along line 42B-42B', of normally-closed valve 4200 in an unactuated state. Flow channel 4202 and control channel 4204 are formed in elastomeric block 4206 overlying substrate 4205. Flow channel 4202 includes a first portion 4202a and a second portion 4202b separated by separating portion 4208. Control channel 4204 overlies separating portion 4208. As shown in FIG. 42B, in its relaxed, unactuated position, separating portion 4008 remains positioned between flow channel portions 4202a and 4202b, interrupting flow channel 4202.

FIG. 42C shows a cross-sectional view of valve 4200 wherein separating portion 4208 is in an actuated position. When the pressure within control channel 4204 is reduced to below the pressure in the flow channel (for example by vacuum pump), separating portion 4208 experiences an actuating force drawing it into control channel 4204. As a result of this actuation force membrane 4208 projects into control channel 4204, thereby removing the obstacle to a flow of material through flow channel 4202 and creating a passageway 4203. Upon elevation of pressure within control channel 4204, separating portion 4208 will assume its natural position, relaxing back into and obstructing flow channel 4202.

The behavior of the membrane in response to an actuation force may be changed by varying the width of the overlying control channel. Accordingly, FIGS. 42D-42H show plan and cross-sectional views of an alternative embodiment of a normally-closed valve 4201 in which control channel 4207 is substantially wider than separating portion 4208. As shown in cross-sectional views Fig. 42E-F along line 42E-42E' of Fig. 42D, a smaller area of elastomeric material is required to be moved during

Fig. 40D. In comparison with the unactuated valve configuration shown in FIG. 42G, FIG. 42H shows the valve 4201 in an actuated position in which the control channel 4207 may under

certain circumstances have the unwanted effect of pulling underlying elastomer 4206 away from substrate 4205, thereby creating undesirable void 4212.

Accordingly, Fig. 42I shows a plan view, and 42J a cross-sectional view along line 42J-42J' of Fig. 42I, of valve structure 4220 which avoids this problem by featuring control line 4204 with a minimum width except in segment 4204a overlapping separating portion 4208. As shown in Fig. 42J, even under actuated conditions the narrower cross-section of control channel 4204 reduces the attractive force on the underlying elastomer material 4206, thereby preventing this elastomer material from being drawn away from substrate 4205 and creating an undesirable void.

While a normally-closed valve structure actuated in response to pressure is shown in Figs. 42A-42J, a normally-closed valve in accordance with the present invention is not limited to this configuration. For example, the separating portion obstructing the flow channel could alternatively be manipulated by electric or magnetic fields, as described extensively above.

## 6. Separation of Materials

In a further application of the present invention, an elastomeric structure can be utilized to perform separation of materials. Fig. 43 shows one embodiment of such a device.

Separation device 4300 features an elastomeric block 4301 including fluid reservoir 4302 in communication with flow channel 4304. Fluid is pumped from fluid reservoir 4306 through flow channel 4308 by peristaltic pump structure 4310 formed by control channels 4312 overlying flow channel 4304, as has been previously described at length. Alternatively, where a peristaltic pump structure in accordance with the present invention is unable to provide sufficient back pressure, fluid from a reservoir positioned outside the elastomeric structure may be pumped into the elastomeric device utilizing an external pump.

Flow channel 4304 leads to separation column 4314 in the form of a separation column 4314 in the form of a separation column 4314. As is well known in the art, separation columns are used to separate mixtures of materials. The elastomeric separation structure is suitable for use with a variety of separation columns, including but not limited to those described above, and may be used in conjunction with a variety of separation techniques, including but not limited to those described above.

protein liquid chromatography (FPLC) and all formats of high pressure liquid chromatography (HPLC). The high pressures utilized for HPLC may require the use of urethane, dicyclopentadiene or other elastomer combinations.

Samples are introduced into the flow of fluid into separation column 4314  
utilizing load channel 4319. Load channel 4319 receives fluid pumped from sample  
reservoir 4320 through pump 4321. Upon opening of valve 4322 and operation of pump  
4321, sample is flowed from load channel 4319 into flow channel 4304. The sample is  
then flowed through separation column 4314 by the action of pump structure 4312. As a  
result of differential mobility of the various sample components in separation matrix  
4316, these sample components become separated and are eluted from column 4314 at  
different times.

Upon elution from separation column 4314, the various sample components pass into detection region 4324. As is well known in the art of chromatography, the identity of materials eluted into detection region 4324 can be determined utilizing a variety of techniques, including but not limited to fluorescence, UV/visible/IR spectroscopy, radioactive labeling, amperometric detection, mass spectroscopy, and nuclear magnetic resonance (NMR).

A separation device in accordance with the present invention offers the advantage of extremely small size, such that only small volumes of fluid and sample are consumed during the separation. In addition, the device offers the advantage of increased sensitivity. In conventional separation devices, the size of the sample loop will prolong the injection of the sample onto the column, causing width of the eluted peaks to potentially overlap with one another. The extremely small size and capacity of the load channel in general prevents this peak diffusion behavior from becoming a problem.

25 The separation structure shown in Fig. 43 represents only one embodiment of such a device, and other structures are contemplated by the present invention. For example, while the separation device of Fig. 43 features a flow channel, load loop, and separation column oriented in a single plane, this is not required by the present invention.

plate of the exoskeleton is shown in Fig. 35C. The length of the head lobe is 0.25 mm, the length above in connection with Fig. 35A-D.

## 7. Cell Pen/Cell Cage/Cell Grinder

In yet a further application of the present invention, an elastomeric structure can be utilized to manipulate organisms or other biological material. Figs. 44A-44D show plan views of one embodiment of a cell pen structure in accordance with the present invention.

Cell pen array 4400 features an array of orthogonally-oriented flow channels 4402, with an enlarged "pen" structure 4404 at the intersection of alternating flow channels. Valve 4406 is positioned at the entrance and exit of each pen structure 4404. Peristaltic pump structures 4408 are positioned on each horizontal flow channel and on the vertical flow channels lacking a cell pen structure.

Cell pen array 4400 of Fig. 44A has been loaded with cells A-H that have been previously sorted, perhaps by a sorting structure as described above in conjunction with Fig. 36. Figs. 44B-44C show the accessing and removal of individually stored cell C by 1) opening valves 4406 on either side of adjacent pens 4404a and 4404b, 2) pumping horizontal flow channel 4402a to displace cells C and G, and then 3) pumping vertical flow channel 4402b to remove cell C. Fig. 44D shows that second cell G is moved back into its prior position in cell pen array 4400 by reversing the direction of liquid flow through horizontal flow channel 4402a.

The cell pen array 4404 described above is capable of storing materials within a selected, addressable position for ready access. However, living organisms such as cells may require a continuous intake of foods and expulsion of wastes in order to remain viable. Accordingly, Figs. 45A and 45B show plan and cross-sectional views (along line 45B-45B') respectively, of one embodiment of a cell cage structure in accordance with the present invention.

Cell cage 4500 is formed as an enlarged portion 4500a of a flow channel 4501 in an elastomeric block 4503 in contact with substrate 4505. Cell cage 4500 is similar to an individual cell pen as described above in Figs. 44A-44D, except that ends 4500b and 4500c of cell cage 4500 do not completely enclose interior region 4500a.

Cell cage 4500 is formed by a plurality of retractable pillars

Specifically, control channel 4504 overlies pillars 4502. When the control channel 4504 is depressed, the pillars 4502 are drawn upward

cell to enter. Upon elevation of pressure in control channel 4504, pillars 4502 relax downward against substrate 4505 and prevent a cell from exiting cage 4500.

5 Elastomeric pillars 4502 are of a sufficient size and number to prevent movement of a cell out of cage 4500, but also include gaps 4508 which allow the flow of nutrients into cage interior 4500a in order to sustain cell(s) stored therein. Pillars 4502 on opposite end 4500c are similarly configured beneath second control channel 4506 to permit opening of the cage and removal of the cell as desired.

Under certain circumstances, it may be desirable to grind/disrupt cells or other biological materials in order to access component pieces.

10 Accordingly, Figs. 46A and 46B show plan and cross sectional views (along line 46B-46B') respectively, of one embodiment of cell grinder structure 4600 in accordance with the present invention. Cell grinder 4600 includes a system of interdigitated posts 4602 within flow channel 4604 which close together upon actuation of integral membrane 4606 by overlying control channel 4608. By closing together, posts  
15 4602 crush material present between them.

Posts 4602 may be spaced at intervals appropriate to disrupt entities (cells) of a given size. For disruption of cellular material, spacing of posts 4602 at an interval of about 2  $\mu\text{m}$  is appropriate. In alternative embodiments of a cell grinding structure in accordance with the present invention, posts 4602 may be located entirely on the above-  
20 lying membrane, or entirely on the floor of the control channel.

## 8. Pressure Oscillator

In yet a further application of the present invention, an elastomeric structure can be utilized to create a pressure oscillator structure analogous to oscillator  
25 circuits frequently employed in the field of electronics. Fig. 47 shows a plan view of one embodiment of such a pressure oscillator structure.

Pressure oscillator 4700 comprises an elastomeric block 4702 featuring flow channel 4704 formed therein. Flow channel 4704 includes an initial portion 4704a

4704a, and a second portion 4704b distal from pressure source 4706. A control channel 4708 is formed in the elastomeric block 4702, and is in fluid communication with flow channel 4704. At a location more distal from pressure source 4706 than via 4708, control



channel 4710 overlies and is separated from flow channel 4704 by an elastomeric membrane, thereby forming valve 4712 as previously described.

Pressure oscillator structure 4700 operates as follows. Initially, pressure source 4706 provides pressure along flow channel 4704 and control channel 4710 through via 4708. Because of the serpentine shape of flow channel 4704b, pressure is lower in region 4704b as compared with flow channel 4710. At valve 4712, the pressure difference between serpentine flow channel portion 4704b and overlying control channel 4710 eventually causes the membrane of valve 4712 to project downward into serpentine flow channel portion 4704b, closing valve 4712. Owing to the continued operation of pressure source 4706 however, pressure begins to build up in serpentine flow channel portion 4704b behind closed valve 4712. Eventually the pressure equalizes between control channel 4710 and serpentine flow channel portion 4704b, and valve 4712 opens.

Given the continuous operation of the pressure source, the above-described build up and release of pressure will continue indefinitely, resulting in a regular oscillation of pressure. Such a pressure oscillation device may perform any number of possible functions, including but not limited to timing.

### 9. Side-Actuated Valve

While the above description has focused upon microfabricated elastomeric valve structures in which a control channel is positioned above and separated by an intervening elastomeric membrane from an underlying flow channel, the present invention is not limited to this configuration. Figs. 48A and 48B show plan views of one embodiment of a side-actuated valve structure in accordance with one embodiment of the present invention.

Fig. 48A shows side-actuated valve structure 4800 in an unactuated position. Flow channel 4802 is formed in elastomeric layer 4804. Control channel 4806 abutting flow channel 4802 is also formed in elastomeric layer 4804. Control channel 4806 is separated from flow channel 4802 by elastomeric membrane portion 4808. A

1. The cross-sectional view of the side-actuated valve structure 4800 in an unactuated position, showing flow channel 4802, control channel 4806, and elastomeric membrane portion 4808.

In response to a build up of pressure within control channel 4806, membrane 4808 deforms and projects into flow channel 4802, thereby closing the valve structure.

within control channel 4806, membrane 4808 would relax back into control channel 4806 and open flow channel 4802.

While a side-actuated valve structure actuated in response to pressure is shown in Figs. 48A and 48B, a side-actuated valve in accordance with the present invention is not limited to this configuration. For example, the elastomeric membrane portion located between the abutting flow and control channels could alternatively be manipulated by electric or magnetic fields, as described extensively above.

### 10. Additional Applications

The following represent further aspects of the present invention: present valves and pumps can be used for drug delivery (for example, in an implantable drug delivery device); and for sampling of biological fluids (for example, by storing samples sequentially in a column with plugs of spacer fluid therebetween, wherein the samples can be shunted into different storage reservoirs, or passed directly to appropriate sensor(s). Such a fluid sampling device could also be implanted in the patient's body.

The present systems can also be used for devices which relieve over-pressure *in vivo* using a micro-valve or pump. For example, an implantable bio-compatible micro-valve can be used to relieve over-pressures in the eye which result from glaucoma. Other contemplated uses of the present switchable micro-valves include implantation in the spermatic duct or fallopian tube allowing reversible long-term or short-term birth control without the use of drugs.

Further uses of the present invention include DNA sequencing whereby the DNA to be sequenced is provided with a polymerase and a primer, and is then exposed to one type of DNA base (A, C, T, or G) at a time in order to rapidly assay for base incorporation. In such a system, the bases must be flowed into the system and excess bases washed away rapidly. Pressure driven flow, gated by elastomeric micro-valves in accordance with the present invention would be ideally suited to allow for such rapid flow and washing of reagents.

FIG. 49 is a schematic diagram of a micro-valve and micro-pump.

FIG. 50 is a schematic diagram of a micro-valve and micro-pump. Such a device can make many passes over the probes of the DNA array. Such a device would give the opportunity to sequentially flow a series of bases or complementary probes the

system is that it would reduce the necessary sample volume, and thereby increase assay sensitivity.

Further applications exist in high throughput screening in which applications could benefit by the dispensing of small volumes of liquid, or by bead-based assays wherein ultrasensitive detection would substantially improve assay sensitivity.

Another contemplated application is the deposition of array of various chemicals, especially oligonucleotides, which may or may not have been chemically fabricated in a previous action of the device before deposition in a pattern or array on a substrate via contact printing through fluid channel outlets in the elastomeric device in close proximity to a desired substrate, or by a process analogous to ink-jet printing.

The present microfabricated elastomeric valves and pumps could also be used to construct systems for reagent dispensing, mixing and reaction for synthesis of oligonucleotides, peptides or other biopolymers.

Further applications for the present invention include ink jet printer heads, in which small apertures are used to generate a pressure pulse sufficient to expel a droplet. An appropriately actuated micro-valve in accordance with the present invention can create such a pressure pulse. The present micro-valves and pumps can also be used to digitally dispense ink or pigment, in amounts not necessarily as small as single droplets. The droplet would be brought into contact with the medium being printed on rather than be required to be fired through the air.

Yet other uses of the present systems are in fluidic logic circuits which offer the advantages of being useable in radiation resistant applications. A further advantage of such fluidic logic circuits is that, being non-electronic, such fluidic logic circuitry may not be probed by electro magnetic sensors, thus offering a security benefit.

Yet further uses of the present invention would take advantage of the ready removal and reattachment of the structure from an underlying substrate such as glass, utilizing a glass substrate patterned with a binding or other material. This allows separate construction of a patterned substrate and elastomer structure. For instance, a glass

substrate could be patterned with DNA and a pump and an elastomer valve and pump

## 11. Additional Aspects of the Invention

Another aspect of the present invention is the use of

elastomeric structure; the use of elastomeric layers to make a microfabricated elastomeric device containing a microfabricated movable portion; and the use of an elastomeric material to make a microfabricated valve or pump.

5 A microfabricated elastomeric structure in accordance with one embodiment of the present invention comprises an elastomeric block formed with microfabricated recesses therein, a portion of the elastomeric block deflectable when the portion is actuated. The recesses comprise a first microfabricated channel and a first microfabricated recess, and the portion comprises an elastomeric membrane deflectable into the first microfabricated channel when the membrane is actuated. The recesses have  
10 a width in the range of 10  $\mu\text{m}$  to 200  $\mu\text{m}$  and the portion has a thickness of between about 2  $\mu\text{m}$  and 50  $\mu\text{m}$ . The microfabricated elastomeric structure may be actuated at a speed of 100 Hz or greater and contains substantially no dead volume when the portion is actuated.

A method of actuating an elastomeric structure comprises providing an  
15 elastomeric block formed with first and second microfabricated recesses therein, the first and second microfabricated recesses separated by a membrane portion of the elastomeric block deflectable into one of the first and second recesses in response to an actuation force, and applying an actuation force to the membrane portion such that the membrane portion is deflected into one of the first and the second recesses.

20 A method of microfabricating an elastomeric structure in accordance with one embodiment of the present invention comprises forming a first elastomeric layer on a substrate, curing the first elastomeric layer, and patterning a first sacrificial layer over the first elastomeric layer. A second elastomeric layer is formed over the first elastomeric layer, thereby encapsulating the first patterned sacrificial layer between the first and  
25 second elastomeric layers, the second elastomeric layer is cured, and the first patterned sacrificial layer is removed selective to the first elastomeric layer and the second elastomeric layer, thereby forming at least one first recess between the first and second layers of elastomer.

As an alternative embodiment of a method of fabricating further comprises  
removal of the first patterned sacrificial layer to form at least one recess along a bottom of  
the first elastomeric layer.

A microfabricated elastomeric structure in accordance with one embodiment of the present invention comprises an elastomeric block, a first channel and a second channel separated by a separating portion of the elastomeric structure, and a microfabricated recess in the elastomeric block adjacent to the separating portion such that the separating portion may be actuated to deflect into the microfabricated recess. 66. Deflection of the separating portion opens a passageway between the first and second channels.

A method of controlling fluid or gas flow through an elastomeric structure comprises providing an elastomeric block, the elastomeric block having first, second, and third microfabricated recesses, and the elastomeric block having a first microfabricated channel passing therethrough, the first, second and third microfabricated recesses separated from the first channel by respective first, second and third membranes deflectable into the first channel, and deflecting the first, second and third membranes into the first channel in a repeating sequence to peristaltically pump a flow of fluid through the first channel.

A method of microfabricating an elastomeric structure comprises microfabricating a first elastomeric layer, microfabricating a second elastomeric layer; positioning the second elastomeric layer on top of the first elastomeric layer; and bonding a bottom surface of the second elastomeric layer onto a top surface of the first elastomeric layer.

## **12. Alternative Device Fabrication Methods**

Figures 1-7A and 8-18 above show embodiments of multilayer soft lithography and encapsulation methods, respectively, for fabricating elastomer structures in accordance with the present invention. However, these fabrication methods are merely exemplary, and variations on these techniques may be employed to create elastomer structures.

For example, Figs. 3 and 4 show fabrication of an elastomer structure utilizing multilayer soft lithography techniques, wherein the recess-bearing face of the

Figure 50 shows elastomeric structure 5410 featuring an alternative orientation of elastomeric layers, wherein recess-bearing faces 5400 and 5402 of first and

larger-sized channel 5408. Alternatively, Figure 51 shows an orientation of elastomeric layers wherein non-recess bearing faces 5500 and 5502 are placed into contact, such that recesses are present on opposite sides of the structure. Such an elastomer structure 5512 could be sandwiched between substrates 5508 and 5510 to produce channels 5504 and 5506 that cross-over each other.

Figures 52A-52D show various views of steps for constructing a fluid channel bridging structure utilizing encapsulation methods. Specifically, Figure 52A shows a cross-sectional view of the formation of lower elastomeric portion 5600 of bridging structure 5602. Figure 52B shows a cross-sectional view of the formation of upper elastomeric portion 5604 of the bridging structure. Figure 52C shows assembly of upper and lower elastomeric portions 5604 and 5600 to form bridging structure 5602, wherein fluid flowing in channel 5606 bridges over cross-channel 5608 through vias 5610 and 5612 and bridge portion 5614 as shown by the arrows. Figure 52D shows a plan view of bridging structure 5602, with bridge portion 5614 of the upper elastomeric is shown in solid, and the features in the underlying lower elastomer layer are shown in outline. This structure requires the formation of vias in the lower layer, but allows multiple liquid streams to flow in a single layer and cross over one another without mixing.

### **13. Composite Structures**

As discussed above in conjunction with the micromirror array structure of Figure 38, the fabricated elastomeric structures of the present invention may be combined with non-elastomeric materials to create composite structures. Fabrication of such composite structures is now discussed in further detail.

Figure 53 shows a cross-sectional view of one embodiment of a composite structure in accordance with the present invention. Figure 53 shows composite valve structure 5700 including first, thin elastomer layer 5702 overlying semiconductor-type substrate 5704 having channel 5706 formed therein. Second, thicker elastomer layer 5708 overlies first elastomer layer 5702. Actuation of first elastomer layer 5702 to drive

wherein thin elastomer layer 5802 is sandwiched between two hard, semiconductor substrates 5804 and 5806, with lower substrate 5804 featuring channel 5808. Again,

actuation of thin elastomer layer 5802 to drive it into channel 5808 will cause composite structure 5810 to operate as a valve.

The structures shown in Figures 53 or 54 may be fabricated utilizing either the multilayer soft lithography or encapsulation techniques described above. In the multilayer soft lithography method, the elastomer layer(s) would be formed and then placed over the semiconductor substrate bearing the channel. In the encapsulation method, the channel would be first formed in the semiconductor substrate, and then the channel would be filled with a sacrificial material such as photoresist. The elastomer would then be formed in place over the substrate, with removal of the sacrificial material producing the channel overlaid by the elastomer membrane. As is discussed in detail below in connection with bonding of elastomer to other types of materials, the encapsulation approach may result in a stronger seal between the elastomer membrane component and the underlying nonelastomer substrate component.

As shown in Figures 53 and 54, a composite structure in accordance with embodiments of the present invention may include a hard substrate that bears a passive feature such as a channels. However, the present invention is not limited to this approach, and the underlying hard substrate may bear active features that interact with an elastomer component bearing a recess. This is shown in Figure 55, wherein composite structure 5900 includes elastomer component 5902 containing recess 5904 having walls 5906 and ceiling 5908. Ceiling 5908 forms flexible membrane portion 5909. Elastomer component 5902 is sealed against substantially planar nonelastomeric component 5910 that includes active device 5912. Active device 5912 may interact with material present in recess 5904 and/or flexible membrane portion 5909.

In the micromirror array embodiment previously described in conjunction with Figure 38, the underlying substrate contained active structures in the form of an electrode array. However, many other types of active structures may be present in the nonelastomer substrate. Active structures that could be present in an underlying hard substrate include, but are not limited to, resistors, capacitors, photodiodes, transistors, insulated field effect transistors (common FET's), amperometric coulometric electrochemical flow sensors, CMOS imaging arrays, CCD cameras, electronic logic, microprocessors, digital logic, D/A converters, analog-to-digital converters, chemical sensors, strain

bimetallic, piezoelectric, shape-memory-alloy based, and others), coils, magnets, electromagnets, magnetic sensors (such as those used in hard drives, superconducting quantum interference devices (SQUIDS) and other types), radio frequency sources and receivers, microwave frequency sources and receivers, sources and receivers for other regions of the electromagnetic spectrum, radioactive particle counters, and electrometers.

As is well known in the art, a vast variety of technologies can be utilized to fabricate active features in semiconductor and other types of hard substrates, including but not limited printed circuit board (PCB) technology, CMOS, surface micromachining, bulk micromachining, printable polymer electronics, and TFT and other amorphous/polycrystalline techniques as are employed to fabricate laptop and flat screen displays.

A composite structure in accordance with one embodiment of the present invention comprises a nonelastomer substrate having a surface bearing a first recess, a flexible elastomer membrane overlying the non-elastomer substrate, the membrane able to be actuated into the first recess, and a layer overlying the flexible elastomer membrane.

An embodiment of a method of forming a composite structure comprises forming a recess in a first nonelastomer substrate, filling the recess with a sacrificial material, forming a thin coat of elastomer material over the nonelastomer substrate and the filled recess, curing the elastomer to form a thin membrane, and removing the sacrificial material.

A composite structure in accordance with an alternative embodiment of the present invention comprises an elastomer component defining a recess having walls and a ceiling, the ceiling of the recess forming a flexible membrane portion, and a substantially planar nonelastomer component sealed against the elastomer component, the nonelastomer component including an active device interacting with at least one of the membrane portion and a material present in the recess.

A method of fabricating a composite structure comprising forming a recess in an elastomer component, the recess including walls and a ceiling, the ceiling forming a membrane portion, the method including the steps of: forming a material layer on the ceiling of the recess, the material layer forming a material portion, the material portion being disposed between the membrane portion and the walls, the material portion may interact with at least one of the membrane portion and the material.



between the elastomeric and nonelastomeric components, to creation of covalent or ionic bonds between the elastomeric and nonelastomeric components of the composite structure. Example approaches to sealing the components together are discussed below, approximately in order of increasing strength.

5                   A first approach is to rely upon the simple hermetic seal resulting from Van der Waals bonds formed when a substantially planar elastomer layer is placed into contact with a substantially planar layer of a harder, non-elastomer material. In one embodiment, bonding of RTV elastomer to a glass substrate created a composite structure capable of withstanding up to about 3-4 psi of pressure. This may be sufficient for many  
10                   potential applications.

A second approach is to utilize a liquid layer to assist in bonding. One example of this involves bonding elastomer to a hard glass substrate, wherein a weakly acidic solution (5  $\mu$ l HCl in H<sub>2</sub>O, pH 2) was applied to a glass substrate. The elastomer component was then placed into contact with the glass substrate, and the composite structure baked at 37°C to remove the water. This resulted in a bond between elastomer and non-elastomer able to withstand a pressure of about 20 psi. In this case, the acid may neutralize silanol groups present on the glass surface, permitting the elastomer and non-elastomer to enter into good Van der Waals contact with each other.

A third approach is to create a covalent chemical bond between the elastomer component and functional groups introduced onto the surface of a nonelastomer component. Examples of derivitization of a nonelastomer substrate surface to produce such functional groups include exposing a glass substrate to agents such as vinyl silane or aminopropyltriethoxy silane (APTES), which may be useful to allow bonding of the glass to silicone elastomer and polyurethane elastomer materials, respectively.

A fourth approach is to create a covalent chemical bond between the elastomer component and a functional group native to the surface of the nonelastomer component. For example, RTV elastomer can be created with an excess of vinyl groups

prevalent on the surface of the rigid substrate, as shown in Figure 1. The surface is modified by etching. In this example, the strength of the bond created between the elastomer

component and the nonelastomer component has been observed to exceed the materials strength of the elastomer components.

While the present invention has been described herein with reference to particular embodiments thereof, a latitude of modification, various changes and  
5 substitutions are intended in the foregoing disclosure, and it will be appreciated that in some instances some features of the invention will be employed without a corresponding use of other features without departing from the scope of the invention as set forth. Therefore, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope and spirit of the  
10 present invention. It is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments and equivalents falling within the scope of the claims.

The following pending patent applications contain subject matter related to  
15 the instant application and are hereby incorporated by reference: U.S. nonprovisional patent application no. 09/\_\_\_\_,\_\_\_\_, entitled "Apparatus and Methods for Conducting Cell Assays and High Throughput Screening" (Atty. docket No. 009195-000200US), filed November 16, 2000; U.S. nonprovisional patent application no. 09/\_\_\_\_,\_\_\_\_, entitled  
20 "Integrated Active Flux Microfluidic Devices and Methods" (Atty docket no. 0G638-US1), filed November 16, 2000; and U.S. nonprovisional patent application no. 09/\_\_\_\_,\_\_\_\_, entitled "Fabrication of Micro and Nano Scale Devices With Soft Materials" (Atty. docket No. 0H944), filed November 16, 2000.

Incorporated herein as part of the present specification is the entire contents of Appendix A, "Monolithic Microfabricated Valves and Pumps by Multilayer  
25 Soft Lithography", Unger et al., Science, Vol. 288, pp. 113-116 (April 7, 2000), which appears herein before the claims and which is to be construed as part of the present specification for all purposes.